ABSTRACT

Title of Document: **COAGULANT USE FOR SEDIMENT REDUCTION IN CONSTRUCTION SITE STORMWATER RUNOFF**

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Sedimentation basins are used at construction sites to reduce sediment-laden stormwater runoff into local water bodies. During storm events, these ponds can have reduced efficiency, causing very turbid water to exit the basin. This project evaluates the performance of coagulants for sediment reduction in construction site runoff in a laboratory setting. The performance of polymers for sediment reduction was assessed. A protocol was developed for coagulant selection at future sites. Four sedimentation basins at a MD 43 construction site in Baltimore County were used in the study. Twelve different coagulants were tested and four were selected for further trials, two anionic, one cationic, plus alum. All samples with coagulants increased sediment reduction efficiency over samples without

coagulant, increasing turbidity reduction from 51% up to 85%. A field coagulant dosing system was designed for future studies.

COAGULANT USE FOR SEDIMENT REDUCTION IN CONSTRUCTION SITE STORMWATER

By

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Dedication

To my wife and parents who have always encouraged me and been fully supportive of my education. Thank you for always being there.

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I would like to express my great appreciation for the assistance and guidance of Dr. Allen P. Davis throughout this project. I would also like to thank the Maryland State Highway Administration for providing the funding for this research.

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Chapter 1. Introduction

During rainfall events, the water reaching the earth's surface either penetrates into the ground, or accumulates and begins a surface flow. This flow is termed stormwater runoff, and has the potential to cause erosion and pollution issues for humans and the environment throughout the world. This process has occurred naturally for billions of years, however, human alterations to the landscape can intensify the problems associated with stormwater runoff. Impervious structures such as roads and buildings create more runoff than natural habitat, but still drain to the same local water bodies. Small streams and wetlands are often overwhelmed with the additional stormwater that travels faster over impervious surfaces and flooding can occur. Stormwater runoff is also a major source of pollution with the ability to mobilize and transport pollutants over long distances. These environmental problems necessitate prevention and control methods such as storm drains, sedimentation basins, and vegetated buffer zones.

Pollutants in stormwater runoff can be classified as chemicals, sediment, or debris. Chemical pollutants are often found in urban and agricultural areas. Oils and toxic metals can be found in stormwater runoff originating from roadsides and parking lots. Fertilizers and pesticides are

common in agricultural runoff. Sediment can be found in any stormwater that passes over earthen materials and is a byproduct of erosion. Rainfall over areas of bare soil create sediment-laden stormwater by destabilizing individual soil particles and allowing them to be transported in the runoff. Debris are large materials that can be transported in fast-moving stormwater. This includes trash, tree branches, leaves, and other similar objects.

The surface over which stormwater is flowing will greatly affect the characteristics and control of the water. Urban stormwater is often fast-flowing due to the relatively smooth and impervious manmade surfaces over which the water flows. This stormwater often contains large amounts of debris and can lead to flash flooding. Stormwater flowing over planted areas is typically slower due to the high surface area of the soil and vegetation in contact with the water and the absorbing qualities of soil and plant roots. Because of this, vegetated buffer zones are often used as a prevention method of erosion alongside streams. Also, the intensity and duration of rainfall can affect runoff flow over soil. Soil can become saturated with water during high intensity or long duration storms and becomes essentially impervious.

Stormwater pollution issues are especially important in Maryland because of the Chesapeake Bay and its tributaries. The Chesapeake Bay is an important estuary for native flora and fauna and some its tributaries are used

as drinking water supplies. Also, many citizens make their living off of the bay and recreation use is very popular. The health of the Chesapeake is thus extremely important to wildlife and the citizens of Maryland. An estuary requires healthy tributaries to maintain high water quality. Stormwater runoff carries fertilizers, pesticides, and sediment into the tributaries of the Chesapeake. Fertilizers and pesticides mostly originate from agricultural lands while the sediment is a byproduct of the rapid erosion and construction occurring throughout the entire watershed. Heavy amounts of construction site sediment can affect the amount of light entering the tributaries, which can be harmful to many aquatic organisms and create biological dead zones (Environment Canada 2004). High turbidity levels inhibit vegetation growth in streambeds and hinder the feeding behavior of schooling fish. Also, suspended solids can irritate fish gills and membranes covering the eyes of aquatic organisms (Environment Canada 2004). Pollution prevention is a necessary method of maintaining high water quality in the Chesapeake Bay.

Construction site stormwater is unique among types of stormwater due to the typical construction landscape. Most construction sites contain vast expanses of barren soil that are frequently disturbed by construction activities, which loosen the soil and allow it to be transported easily by runoff. These conditions lead to heavy sediment-laden runoff. This is a

common pollution issue at many construction sites (McLaughlin 2002). Sedimentation basins are the most common management practice for sediment control at construction sites. In areas where stormwater diversion to a basin is difficult, silt fences and straw bales are used to prevent large amounts of sediment from leaving the construction site.

Sedimentation basins represent a stormwater runoff management practice used in areas with significant erosion, such as construction sites. For a particular drainage area, all of the stormwater runoff is diverted to the basin. The water then builds up in the basin and moves slowly to a defined outlet. This allows for gravitational sedimentation of suspended sediment particles. This will happen with all particles denser than water, given adequate time. The settling velocity in water of each individual particle varies based on the particle radius and density. With larger and denser particles, the settling occurs more quickly. The density of the particle depends on its chemical makeup. Sand, silt, and clay make up the common components of sediment in runoff and are of equal density, but vary in particle radius. Sand is the largest particle size category and settles very quickly, while clay and silt are smaller and remain suspended longer in solution.

The inflows to the basin are often constructed of riprap. The riprap consists of large stones and rocks placed in the path of the incoming runoff. The large stones decrease the velocity by forcing the runoff to traverse a longer pathway into the basin. If the water level in the sedimentation basin rises above a certain point, water begins draining from an outflow. The outflow often consists of perforated pipe in the basin that drains to a local waterway. This pipe is covered with a filter cloth that collects a portion of the remaining suspended particles. There is also a concrete weir at the outlet for overflow to occur during high intensity storm events. The weir offers a controlled response to a potential flooding problem in the basin. However, this can lead to significant amounts of suspended sediments being released into a local waterway due to insufficient particle settling time. An example of the sedimentation process can be seen in Figure 1.1.

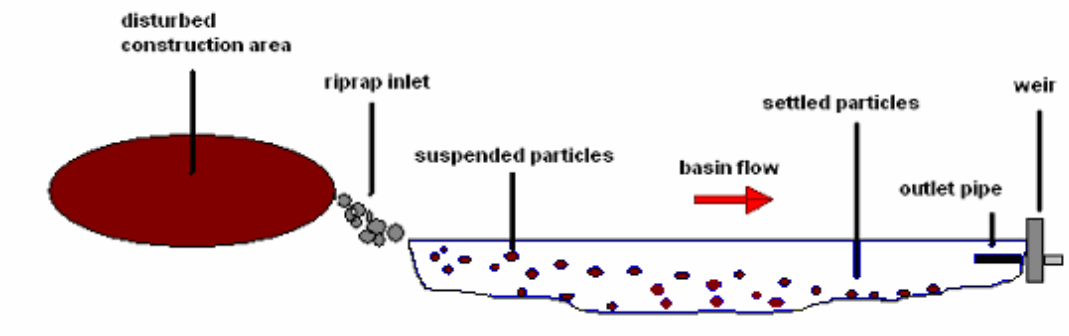

Figure 1.1. Construction Site Sedimentation Basin

Coagulants are chemicals that aid in the sedimentation process. The coagulants stimulate interactions either between or with the suspended sediment particles. These interactions cause the formation of flocs, which are agglomerations of suspended particles. The flocs increase the effective size of the suspended particles and often increase the settling velocity. The addition of coagulants has the ability to increase efficiency of the sedimentation process. Coagulants are regularly used in water and wastewater treatment, but little study has been completed in construction site sedimentation basins.

The specific objectives of this project were to study the use of polyacrylamide (a common water treatment polymer) and other coagulants as a method to reduce sediment in construction site stormwater discharge and to develop a protocol by which appropriate coagulants could be selected for use at specific sites. A literature review on the use of polymers at construction sites is presented. A polymer was selected for study and field studies were completed at a MD 43 construction site with the chosen polymer. The specific project goal was to identify a coagulant and application method to reduce sediment from construction site stormwater basin discharges. Parameters needing study include type of coagulant, dose, effectiveness, application method, and environmental fate of the coagulant

chemical. Laboratory studies were completed and a selection protocol was developed for future field studies. A field study design was also proposed for future studies and implementation.

The construction site employed in this study was in White Marsh, MD. The Maryland State Highway Administration was extending MD 43 from US 40 east to MD 150. Numerous sedimentation basins were constructed for this project and four were selected for study: Basins 6, 7, 8, and 9. Basins 6 and 7 drained into Windlass Run, while basins 8 and 9 drained to a wetland (Figure 1.2). All basins were surrounded by active construction during the study and thus were considered as typical of construction site sedimentation basins. Silt fences were employed to divert stormwater to regulated riprap inflows. Basin 6 also contained an inflow from a storm drain located on a portion of completed roadway.

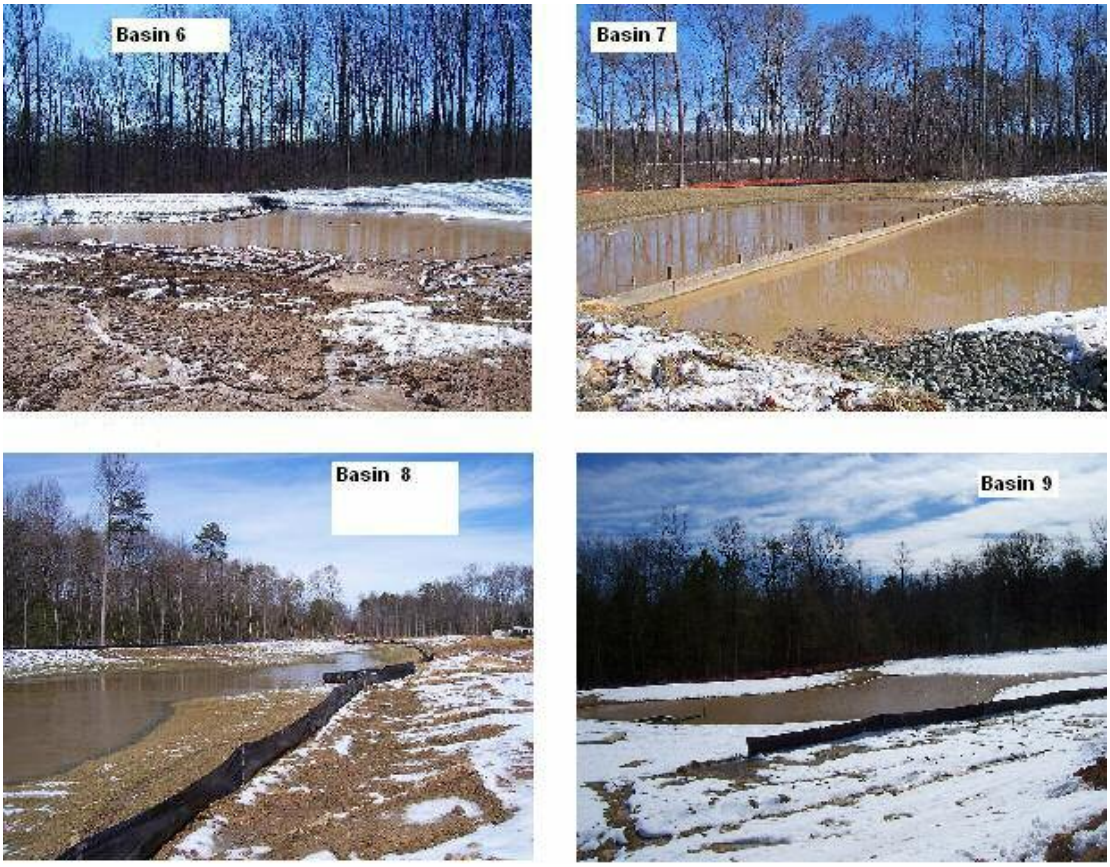

Figure 1.2. Photos of site basins at MD 43 construction site in Baltimore County, winter 2005

Chapter 2. Literature Review

2.1. Sedimentation

Sedimentation is a solid-liquid separation process. From a water treatment perspective sedimentation is used mainly to lower the solids concentration before filtration (Gregory et al. 1999). For sedimentation basins, the solids concentration is lowered before discharge to local streams and wetlands. The term settling is used to describe particles falling through a liquid under the force of gravity (Gregory et al. 1999). When particles are suspended they may form flocs with other suspended particles, which increases their settling rate.

Stokes Law physically defines the sedimentation process. The terminal settling velocity of a particle (V_t) can be calculated using (Weber 2001):

$$V_t = \frac{gd^2(\rho_p - \rho_m)}{18\mu} \qquad (2.1)$$

The terminal settling velocity is a function of gravitational acceleration, g, particle diameter, d, particle density, ρ_p, fluid density, ρ_m, and fluid viscosity, μ. The flow rate, Q, and cross-sectional area, A_c, of a sedimentation basin are related to the critical settling velocity.

$$V_c = \frac{Q}{A_c} \tag{2.2}$$

If the terminal settling velocity of a particle is less than the critical settling velocity, the particle can be expected to settle in a given basin.

2.1.1. Sedimentation Basin Construction

The Maryland Department of the Environment (1994) requires sedimentation basins to be constructed to control runoff and sediment from large drainage areas where small sediment traps are inappropriate. The shape of the basin is recommended to have a 2:1 length to width ratio and be wedged shaped with a narrow inlet and wider outlet. Baffles may be used when conditions cannot be met. The side slopes of the basin must be between 0.2 and 0.5 and be stable in all weather conditions. The volume of the basin must be at least 499 m^3 (8892 ft^3) per hectare of drainage area. The surface area of the basin in hectares is related to the 10-year storm runoff in liters per second by ratio greater than or equal to 5×10^{-5}. Settled sediment must be removed from the basin and a disposal site must be chosen during the planning process. The location must not allow the sediment to erode into a stream or floodplain. There are no specific water quality requirements for water discharged from the basin.

2.2. *Coagulation*

Coagulation is a process that is an essential component of water and wastewater treatment. It is defined as the increase in tendency of small particles in aqueous solution to attach to one another and to attach to surfaces (Letterman et al. 1999). The physical process of producing interparticle contacts is termed flocculation. A floc is an agglomeration of small particles. Coagulants are used to destablize particle suspensions and enhance the rate of floc formation. Today in water treatment, the list of coagulants is extensive and includes alum, ferric iron salts, and synthetic and natural organic compounds. Enhanced floc size will often increase sedimentation rate.

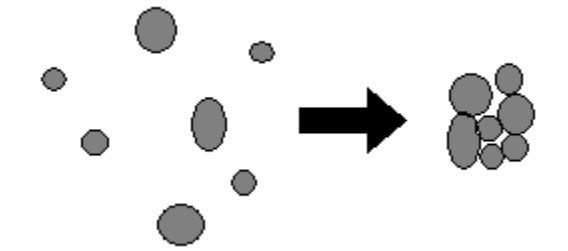

Figure 2.1. Flocculation: suspended particles attracted to one another and forming a floc

2.3. *Polyacrylamide*

Polyacrylamides are a class of water-soluble synthetic compounds formed by the polymerization of acrylamide monomer. The molecular weight of these compounds can vary widely, from less than 10^5 g/mol to greater than $5x10^6$ g/mol (Barvenik 1994). The polymer can be cationic, anionic, or nonionic. Cationic and anionic polyacrylamides are produced by the copolymerization of acrylamide and a suitable cationic or anionic comonomer (Figure 2.1). Nonionic polyacrylamides are homopolymers of identical acrylamide units with a slight anionic charge due to hydrolysis (Barvenik 1994). All polyacrylamides contain residual acrylamide, but it is regulated to <0.05 % by weight.

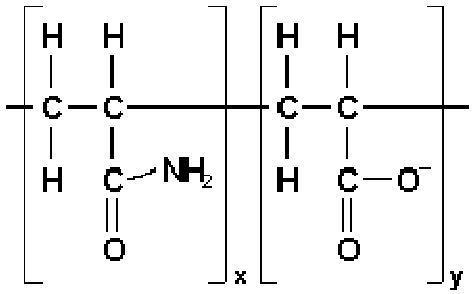

Figure 2.2. Anionic Polyacrylamide www.naic.org/Meeting/2001/UseofPAM.html

2.3.1. Polyacrylamide Sorption Mechanisms

The sorption mechanisms of polyacrylamide have been studied since they were first used for coagulation purposes in the 1950s. The sorption mechanism of a coagulant is important for determining how a coagulant can be most effective. Hydrogen bonding was the first mechanism proposed, with a hydrogen bond between the amide group of the polymer and the free hydroxyl group of the absorbent surface (Kohl and Taylor 1961). Another suggested mechanism was a ligand exchange in which the carboxylic group of the polymer enters the inner coordination layer of aluminum ions on the edge of the absorbent surface to form a coordination complex (Theng 1982). However, at practical field pH values between 5 and 9, both the anionic polyacrylamide and sediment particles are negatively charged. Electrostatic repulsion prevents polyacrylamide sorption through hydrogen bonding and ligand exchange in this pH range (Lu et al. 2002). The sorption mechanism in this pH range is entirely governed by competition between polymer attractive interactions with surfaces and repulsive electrostatic forces. The polyacrylamide sorption increases with reduced repulsive forces and this can be accomplished through cation masking or bridging (Laird 1997, Lu et al. 2002). In aqueous solutions, the cation bridging mechanism is hypothesized

to be an "outer sphere" complex formed between an anionic polymer group and an exchangeable cation through a water molecule (Shainberg 1990). In average soil solutions, Na^+, K^+, Ca^{2+}, and Mg^{2+} are commonly found cations (Wolt 1994). In Lu et al. (2002), calcium and magnesium ions increased polyacrylamide sorption better than sodium and potassium ions. However, overall efficiency varied with soil structure and composition.

2.3.2. Polyacrylamide Uses in Water Treatment and Erosion Control

Polyacrylamides were first used in the 1950s when the nonionic form was used to separate silica fines from dissolved uranium ores in acidic systems (Barvenik 1994). Now polyacrylamides are used as flocculant aids to primary coagulants in a variety of systems. Anionic forms are used in mineral and coal processing, petroleum production, papermaking, water treatment, and food processing. The cationic forms are used for flocculation of sewage sludge and various industrial wastes (Barvenik 1994). The use of polyacrylamides for erosion control is relatively recent, but now $4x10^5$ ha/year of agricultural land are treated with polyacrylamide in the United States (Vacher et al. 2003). Polyacrylamide stabilizes soil aggregates, has been shown to prevent surface seal formation, and increase infiltration of irrigation

water and rainfall (Vacher et al. 2003). With furrow irrigation systems, polyacrylamide is applied to the irrigation water and applied through a sprinkler system (McLaughlin 2002). At construction sites, polyacrylamide has been added directly to the soil to prevent erosion. It can be applied in dry granular form placed on the soil, or in solution and sprayed onto the soil. In Washington state, Minton and Benedict (1999) treated runoff water directly with polymers. This process resembled a water treatment plant. A storage basin captured stormwater from the drainage area and polymer was added during controlled release of stormwater from the storage basin to a treatment cell.

2.3.3. Polyacrylamide Studies in Natural Settings

The effectiveness of polyacrylamide on erosion control is related to the clay content of the soil and the molecular weight and charge density of the polymer (Vacher et al. 2003). A North Carolina study found polyacrylamide to significantly increase total infiltration under rainfall, reduce surface hardness, and reduce sediment entrainment and erosion by both rainfall and overland flows when applied directly to the soil surface (McLaughlin 2002). In that study, the Cytec Superfloc A-100 ranked among the top three flocculants for 10 of 13 sediment sources and was the top flocculant for 5

sources. The Superfloc polymers were applied at concentrations of 0.5, 1.0, and 2.0 mg/L to soil solutions in the laboratory and reduced turbidity by up to 99% at optimal concentrations for the soil type.

A Wisconsin study tested three methods of application. The wet method involved mixing 2.25 g of polymer with 5 L of water and application with a sprayer or sprinkler at a rate of 22.5 kg/ha. The dry method directly applied 2.25 g of granular polymer to a square meter soil plot. The mulch method used a polymer solution in conjunction with a mulch/seeding mix. The mixture was applied using the same methodology as a typical mulching process. In this study, the mulch method was most effective and reduced sediment yield by 93%. The least effective application method, polymer-mix solution applied to moist soil, reduced sediment yield by 77% (Roa-Espinosa et al. 1999).

In Washington, Tobiason et al. (2000) found that mixing 120 mg/L polymer with hydromulch produced the highest turbidity reduction, 94-99%, but it was more cost-effective to use polyacrylamide directly in 40-80 mg/L solution applied at a rate of 6700 L/ha (720 gal/acre). The turbidity reduction was 72% and 82% with 40 and 80 mg/L, respectively (Tobiason et al. 2000). Dry polymer was also effective but required 10 times the material by weight. Another Washington study treated the runoff as opposed to the soil. After

the runoff was collected in a storage pond, it was pumped into a treatment cell where polymer was added at a concentration of 10-60 mg/L in the basin. The treatment cell process was able to reduce turbidity from >1000 NTU to <50 NTU for 20-60 mg/L polymer (Minton and Benedict 1999).

In New Zealand, a rainfall-driven dosing device was used in stormwater basins. Rain would be collected in a tray and flow to a displacement tank. The displacement tank floated in a polyaluminum chloride solution and the solution was displaced into the basin when rainfall filled the tank. Sediment removal increased from 81 to 97% in one basin and 69 to 93% in another basin after the input of coagulant (Auckland Regional Council 2003). Another trial in New Zealand placed polymer bricks in the inlet channels of the sediment basins. The runoff was diverted into the channels where it would come into contact with the polymer before entering the pond. The use of the polymer bricks was effective at reducing Total Suspended Solids (TSS), a laboratory test measuring suspended particles greater than 1 μm in diameter, by up to 50% for inflows of 2 L/s per brick used. However, the bricks often broke and washed into the ponds where they were not effective. Also, if underdosed, the polymer did not significantly reduce TSS. New bricks would need to be placed before each

storm event after estimating the expected inflow rate (Auckland Regional Council 2003).

2.3.4. Polyacrylamide Environmental Fate and Toxicity

The toxicity of polyacrylamide in the environment is dependent upon the charge of the molecule, while the environmental fate is similar for all the polymers. Polyacrylamide can be degraded in soil systems by cultivation, sunlight, mechanical breakage in the soil, chemical hydrolysis, salt, and temperature effects (Barvenik 1994, Seybold 1994). This rate has been estimated at ten percent per year (Barvenik 1994). The polymers have shown to be resistant to microbial degradation (Seybold 1994). Polyacrylamide is nontoxic to humans when ingested, but can be a mild skin irritant. The anionic form has been found to have no adverse effects on fathead minnows, rainbow trout, yellow perch, and bluegill at concentrations of 1000 mg/L for 5 days and 100 mg/L for 90 days (Seybold 1994). Anionic polyacrylamide was only found to be toxic to fish at concentrations where the water was made viscous and extreme doses of 1-5 % dry weight of the soil can affect plant growth. Cationic polyacrylamide can bind to the gills of fish at concentrations of 0.3-10 mg/L.

The major concern with polyacrylamide is the potential for the acrylamide monomer to accumulate in the environment. Acrylamide is a neurotoxin to humans and highly toxic in the environment. Seybold (1994) says that while acrylamide is released into the environment via polyacrylamide products, it is biodegradable and does not accumulate in soils. McLaughlin (2002) states that polyacrylamide will not regenerate the acrylamide monomer in the environment.

2.4. Alum

Alum is aluminum sulfate that is often used for coagulation in water and wastewater treatment. It has the chemical formula $Al_2(SO_4)_3 \bullet nH_2O$. The number of water molecules of hydration (n) varies, but is usually 14 or 18 for coagulation purposes. On average, alum is 4.3 wt % aluminum and has a calculated acidity of 0.111 meq/mg Al (Letterman et al. 1999). In water and wastewater treatment, alum has been added as a coagulant to turbid water for over 100 years (Harper et al 2002). Typically it is added as a solid hydrate directly to the water to be treated. More recently, alum has been added to lakes and stormwater retention ponds as a coagulant, but also for phosphorus removal.

2.4.1. Chemistry of Alum Coagulation

The primary use of alum is for coagulation. When alum is added, the desired result is an increased sedimentation rate. To increase the sedimentation rate, the particles must increase in effective size through the formation of flocs. Alum precipitates aluminum hydroxide onto the particle which destabilizes the particle suspension to form flocs through charge neutralization. The vast majority of natural particles have an inherent charge. This charge is due to isomorphic substitution, the ionization of amphoteric surface groups for inorganic molecules, or the ionization of organic functional groups in organic molecules. This charge is pH dependent and is negative for most particles at natural pH levels. The pH at which a particle charge changes from positive to negative is known as the pH_{zpc}. For clay, sand, and bacteria, the pH_{zpc} is around 2. For proteins and other organic matter, it is around 4.5 (Weber 2001). Alum is an effective coagulant because aluminum hydroxide has a pH_{zpc} of 8.5 so it maintains a positive charge at most natural pH levels. Once the particle is neutralized, van de Waals attractive forces begin to dominate in the system. The flocs begin to form and the particles settle out.

When alum is added to water, a series of hydrolysis reactions takes place before aluminum hydroxide is formed (VanLoon and Duffy 2000). The hydrolysis consists of the successive deprotonation of the hydrate molecules around the aluminum.

$$Al(H_2O)_6^{3+}\ (aq) + H_2O \rightarrow Al(H_2O)_5(OH)^{2+}\ (aq) + H_3O^+ \qquad (2.3)$$

$$Al(H_2O)_5(OH)^{2+}\ (aq) + H_2O \rightarrow Al(H_2O)_4(OH)_2^{+}\ (aq) + H_3O^+ \qquad (2.4)$$

$$Al(H_2O)_4(OH)_2^{+}\ (aq) + H_2O \rightarrow Al(H_2O)_3(OH)_3\ (s) + H_3O^+ \qquad (2.5)$$

$$Al(H_2O)_3(OH)_3\ (s) + H_2O \rightarrow Al(H_2O)_2(OH)_4^{-}\ (s) + H_3O^+ \qquad (2.6)$$

The extent of the overall reaction is dependent upon the availability of proton acceptors, usually Bronstead bases. In water, a high alkalinity will often provide the necessary Bronstead bases for the reaction to proceed fully. In domestic wastewater, high alkalinity is generally not an issue. However, with stormwater the pH and alkalinity can be variable depending on the geography, soil, and acidity of the rainfall. Very little if any polymerization occurs during the hydrolysis (Van Benschoten and Edzwald 1990a). If bicarbonate is used as the Bronstead base, the overall reaction that takes place is (VanLoon and Duffy 2000):

$$Al(H_2O)_6^{3+}\ (aq) + 3HCO_3^- \rightarrow Al(OH)_3\ (s) + 3CO_2\ (g) + 6H_2O \qquad (2.7)$$

An example of a potential charge neutralization of a silica group ($\equiv SiO_2$) by alum through polymer adsorption can be seen in equation 2.8 (Letterman et al. 1999). Silica can be a stand-alone molecule or part of a larger molecule:

$$Al^{3+} + \equiv SiO^- + 2H_2O \rightarrow \equiv SiO\text{-}Al(OH)_2^+ + 2H^+ \qquad (2.8)$$

Silica gains its negative charge from negative surface sites such as $\equiv SiO^-$. The positively charged $Al(OH)_2^+$ ion bonds with the surface site and neutralizes the charge. A 2005 study showed alum to have a rapid affect on lowering pH, alkalinity, and dissolved silca concentrations in lakes (Berkowitz et al. 2005).

The removal of fulvic acid (FA, natural organic material in water) is slightly more complicated. When alum is added to remove fulvic acid, it is postulated that a complex of $Al(OH)_{2.7}FA_{0.64}$ is formed (Van Benschoten and Edzwald 1990b). This was based on experiments at pH levels of 5 and 7. This same study also determined that removal of fulvic acid is greater at pH 7 than at pH 5.

Another method through which aluminum hydroxide can aid the settling of suspended particles is through a "sweeping floc." If a significantly large dose of alum is provided, the aluminum hydroxide forms large flocs with itself. The flocs then begin to settle and entrap other suspended particles during the descent. This method is very effective and will reduce the turbidity of the solution.

When adding alum to a solution, it is advantageous to have the pH between 5.5 and 7.5. This ensures that aluminum hydroxide will be precipitated rapidly and that the dissolved Al(III) concentration will remain low. A study by Van Benschoten and Edzwald (1990a) demonstrated that Al solubility was adequately described with only three monomeric species: Al^{3+}, $Al(OH)^{2+,}$ and $Al(OH)_4^-$ The U.S. EPA maintains a secondary drinking water standard for aluminum at 1.9-7.4 x 10^{-6} M (0.05-0.20 mg/L). These levels can be reached at pH 5 or 8. It has been reported that at pH levels less than 5.5, 3.7 x 10^{-6} M (0.01 mg/L) Al may be toxic to trout (Berkowitz et al. 2005). With alum addition to stormwater, pH will likely decline slightly. This has the potential to decrease the pH and increase the dissolved aluminum concentration to unsafe levels for living organisms.

For coagulation in drinking water treatment, several pH ranges have been cited as optimum for alum without testing results. Clark et al. (1999)

and the US Army Corps of Engineers (2001) state that alum is most effective as a coagulant in the pH range of 5.5 to 8.0. Davis and Cornwall (1998) list the optimum pH range as 5.5 to 6.5.

Besides pH, the temperature of the system should also be considered when adding alum as a coagulant. Temperature has been shown to have an effect on turbidity, electrophoretic mobility, and Al solubility (Van Benschoten and Edzwald 1990a). This difference can be attributed to the hydroxyl ions involved in the hydrolysis. At constant pH, the hydroxyl ion concentration changes with temperature as the ion product of water changes with temperature. With colder temperatures, the solubility of aluminum hydroxide decreases at constant pH, but is less effective as a coagulant. However, adverse effects of colder temperatures can be compensated with an increase in pH.

2.4.2. Alum Turbidity Reduction

While the primary focus of most stormwater studies investigating alum addition has been phosphorus removal, a reduction of turbidity can be

a benefit of alum use as well. Harper et al. (2002) were able to reduce turbidity and total suspended solids to greater than 97 % removal using alum in urban stormwater. This process could prove to be very useful in the treatment of stormwater sedimentation ponds that have been overloaded. The pH of stormwater can be variable, but is often within the optimum range of 5.5-7.5 for alum-induced coagulation.

Chapter 3. Methodology

3.1. Coagulants

3.1.1. Polymers Used

The literature review noted that several construction sites had shown success at reducing construction site erosion with the use of polyacrylamide. The nonionic and anionic forms are nontoxic to aquatic organisms unlike the cationic form. Based on previous studies, anionic polyacrylamide was chosen to be the focus in this study. Polyacrylamides from Cytec Industries, West Paterson, NJ, were used in the field trial and the lab trials. Polymers obtained included Superfloc N-300, a nonionic polyacrylamide, and Superflocs A-100, A-110, A-120, A-130, A-130V, and A-150, all anionic (Table 3.1). The anionic charge increases with the higher-numbered polymers. Cationic polymers C-446, C-448, C-496, and C-498 were also tested for comparison purposes. For the field trial, A-100 was used because it was compatible with more soil types than any other polymer used during the North Carolina study (McLaughlin 2002).

Table 3.1. Polymer Characteristics (Cytec Industries, West Paterson, NJ)

Polymer	Charge	Molecular Weight
N-300	< - 1 %	High
A-100	- 7 %	High
A-110	- 16 %	High
A-120	- 25 %	High
A-130	- 33 %	High
A-130V	- 34 %	Ultra High
A-150	- 50 %	High
C-446	+ 35 %	Medium
C-448	+ 55 %	Medium
C-496	+ 35 %	High
C-498	+ 55%	High

3.1.2. Alum

Alum was chosen as an alternative coagulant after the initial polymer laboratory studies. It was selected based on the known use and performance in water and wastewater treatment as a coagulant. Also, a preliminary lab trial demonstrated effectiveness with stormwater collected from the MD 43

field site. The alum used in the laboratory studies was $Al(OH)_3 \bullet 18H_2O$, manufactured by Fisher Scientific.

3.2. Basin Characteristics

The basins studied were chosen by the Maryland State Highway Administration. Basins 6, 7, 8, and 9 were chosen because ongoing construction would continue in their drainage areas throughout the study. Basins 6 and 7 emptied into Windlass Run, while basins 8 and 9 drained into a shared wetland. Each basin studied at the MD 43 site possessed characteristics that identified it as unique to the others. Basin 6 had two inflows and a rectangular weir outflow. It was the smallest basin in the study. Basin 7 also had 2 inflows and a rectangular weir outflow, but also had a large baffle in the middle of the basin to extend the retention time of the runoff and increase mixing. Basin 8 only had one inflow and was long and narrow. The mixing characteristics of that basin were expected to be similar to those of a plug-flow reactor. Basin 9 was unique in that it had a square overflow weir as opposed to a rectangular weir. Details are summarized in Table 2.

Table 3.2. Sedimentation Basin Characteristics

Basin	Surface Area (m^2)	Inflows	Outflow
Basin 6	2376	2	Rectangular weir
Basin 7	2836	2	Rectangular weir
Basin 8	5004	1	Rectangular weir
Basin 9	3975	1	Square overflow weir

3.3. Analytical Methods

3.3.1. Total Suspended Solids

A Total Suspended Solids (TSS) measurement was made for all samples taken. The procedure was performed following Standard Methods 2540D (APHA et al. 1999). This measurement collected all suspended solids larger than 1 μm on a 2.5 cm diameter glass fiber filter (Pall Life Sciences) that was dried to constant weight at 103-105^{o}C and weighed.

3.3.2. Total Dissolved Solids

A Total Dissolved Solids (TDS) measurement was made in the laboratory trials. This procedure was performed following Standard Methods 2540C (APHA 1999). The TDS measurement evaporated the effluent

passing through a 1 μm filter, collecting all dissolved particles as well as suspended particles smaller than 1 μm. The addition of TSS and TDS produces a Total Solids (TS) measurement that was used to standardize the data. Standardization was needed in the first field trials because the samples contained significant suspended particles smaller than 1 μm. These particles would pass through the TSS filter on the samples prior to addition of coagulant. After coagulant was added some of these particles would flocculate, but not settle. They would then be captured by the TSS filter and the results between the coagulant sample and control sample would not be comparable.

3.3.3. Turbidity

Turbidity measurements were taken for the laboratory trials. The measurement was taken using a Hach 2100A turbidimeter and followed Standard Methods 2130B (APHA et al. 1999). The turbidimeter was calibrated using the 17 NTU standard for measurements between 10 and 100 NTUs and the 2 NTU standard for measurements between 1 and 10 NTUs.

3.4. Field Studies

3.4.1. Without Polymer

A control study was performed at the field site without polymer to assess the settling in the basins. On May 5, 2005, samples were collected every hour for six hours during a rainfall event from three points in each basin. The sampling locations were, for each basin: the major input, next to the clothed outlet pipe, and the outflow. During initial observations of the basins, the clothed outlet pipe was seen collecting significant sediment. A measurement was taken at the clothed pipe as well as the outflow to determine the effect of sedimentation versus the effect of the clothed pipe. The samples were collected in 500 mL plastic bottles and transported to the Environmental Engineering laboratory at the University of Maryland, College Park in a cooler. Each bottle was rinsed with basin water before the sample was taken to lessen contamination of the sample. At the lab, TSS measurements were taken for all samples.

3.4.2. With Polymer

A study was performed at the field site with polymer to assess the feasibility of a large-scale dosing of a basin. On June 3, 2005, Superfloc A-100

was added to basin 7, with basin 6 used as a control. Six doses of 144 g of polymer were used for a total of 0.864 kg and a total estimated dose of 1 mg/L in the basin. The dose was calculated using the design volume for basin 7. Each dose of polymer was placed in a bucket with the bucket then filled with outflow water. The polymer was mixed in the water and thrown into the basin. The doses were spread throughout the basin to encourage mixing. A day with light rain was chosen for testing so there would be a steady inflow into the basins. Samples were collected and transported in the same manner as in the field study without polymer. Samples were taken just before the polymer was input into basin 7, and every hour for the following five hours. In basin 6, no sample was taken from the outflow because there was very little water exiting the basin. At the lab, TSS measurements were taken for all samples.

3.5. Laboratory Tests

At the site, 500 mL plastic bottles were filled from the edge of basin 9 on June 28, July 20, October 10, November 23, and December 14, 2005, basin 8 on July 5, and October 22, 2005, and basin 6 on November 23, 2005. Samples were collected following rain events to insure relatively high turbidity. At the lab, the samples were mixed into labeled plastic bottles, each sample 500

mL. A TSS measurement was taken for each of the samples as well as a TDS measurement. The appropriate dose of the polymer (D) was calculated using the desired polymer concentration (X), the volume of the sample (V), and the stock solution concentration (S).

$$D = (XV) / S \quad (3.1)$$

The appropriate dose of polymer was then added to each sample from a stock solution of 500 mg/L. A mini-vortex was used to mix the samples after addition for three minutes. After two hours of settling, TSS and TDS measurements were again taken by siphoning liquid from the top of the sample. After 24 hours of settling, the collection for TSS and TDS was repeated. An additional sample was taken at this time for a turbidity measurement. Each coagulant was tested at multiple doses to determine the optimum dose for the stormwater sample.

The times of 2 and 24 hours were used as a comparison of settling rates for coagulants and natural settling. In theory, the coagulants take effect immediately after mixing, so the 2 hour settling time was used to see if the coagulant made a significant impact. A 24 hour settling time is more indicative of a natural retention time in a large sedimentation pond and was used as an overall comparison of natural settling versus coagulant settling.

3.6. Coagulant Selection Protocol

The purpose of the comparison trial was to select an optimum coagulant and application dose for use in construction site sedimentation basins. Sediment characteristics vary with each individual site, so the coagulant selection protocol should be followed to determine the optimum coagulant and dose for use at a particular site. This protocol was also used for the pH study to maintain similar initial TSS and turbidity conditions over all pH ranges.

For the protocol tests, soil was collected from the drainage area of basin 7 to nearly fill a 5-gallon bucket. This insured there was enough soil for multiple trials. The soil was allowed to air dry in the bucket overnight before being sieved to 150 μm sieve size. The action of the coagulants must be focused on clays and silts, and not sand particles for proper comparison to natural conditions. With sieve sizes larger than 150 μm, the soil settles too easily due to high sand content and large flocs of clay and silt. Sieve sizes smaller than 150 μm leave minimal soil to work with.

Stormwater was collected in 500 mL plastic bottles from basin 7 on April 14 and May 4, 2006 for each coagulant tested, plus a no-coagulant control. These samples were not collected after storm events so the water was

relatively clean with low TSS and turbidity values. For the pH study, small amounts of 0.1 M HCl or 0.1 M NaOH were added to the samples to adjust the pH. The ambient pH of water collected on May 4, 2006 was 7.45.

Three g of air-dried sieved soil were added to 500 mL of the stormwater collected from the basin. It was rapidly mixed by shaking the bottle for 5 seconds and allowed 1 minute for initial settling of sand and other fast-settling particles. This allowed for clay and silt particles to remain suspended in the sample and be the focus of settling by chemical coagulation. Measurements were taken of TSS, TDS, and turbidity for the initial conditions.

Coagulants were selected for the comparison trial using the results for the previous laboratory trials. The percent removal of TS and turbidity of the most effective dosage of each coagulant were compared to the percent removal TS and turbidity of the control sample under the same conditions. Those values were taken as a ratio for each coagulant. Coagulants with the lowest ratios were determined to be more effective than other coagulants at this site. Coagulants chosen for this site were A-100, A-110, C-448, and alum.

Coagulants were made into stock solutions with concentrations large enough so that less than 5 mL of coagulant needed to be added to the 500 mL sample. Stock solutions for A-100 and A-110 had concentrations of 500 mg/L,

C-448 had a concentration of 660 mg/L and alum had a concentration of 11,000 mg/L. The appropriate coagulant dose was input via pipet into water and rapidly mixed using the same shaking method from the initial testing. Thirty minutes of settling were allowed before repeating TSS, TDS, and turbidity measurements.

Chapter 4. Results

4.1. Initial Field Tests

The first field study on May 5, 2005 compared the settling effects of the basins. The TSS measurements taken over six hours at each point in the basin were averaged and are plotted in Figure 4.1. Basin 6 had very low TSS (mean = 55 mg/L) and showed no evidence of settling. Basins 7 and 8 demonstrated settling in the basins with little effect between the clothed pipe and the outflow. Basin 9, however, had very high TSS (mean = 964 mg/L). A decrease in TSS was seen from settling and from the clothed pipe at the outflow. The TSS in the outflow varied significantly over the 6-hour period of study, but averaged lower than the samples taken from the clothed pipe.

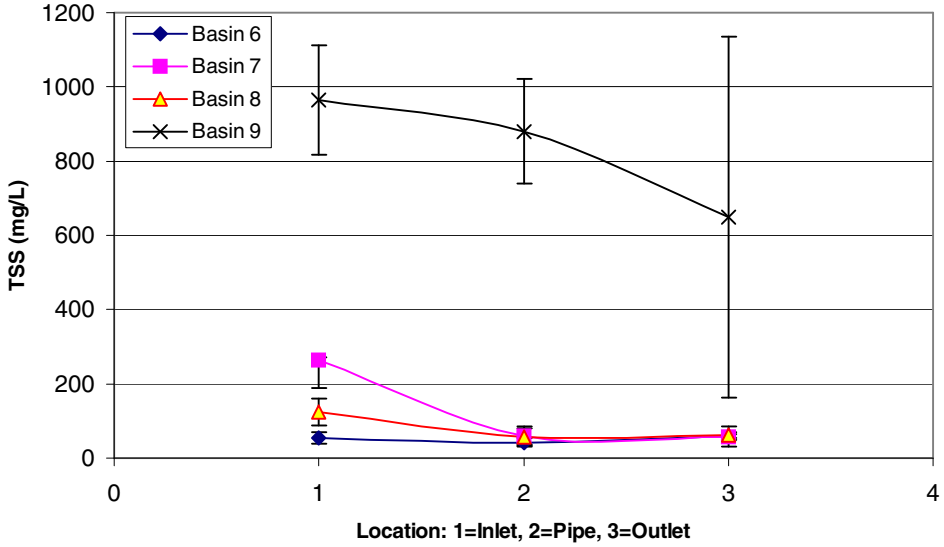

Figure 4.1 Average TSS measurements in MD 43 sediment basins from May 5, 2005 field test; error bars +/- 1 standard deviation

The next field study on June 3, 2005 was done with A-100 polyacrylamide addition. A-100 was chosen because of its success with multiple soil types in a North Carolina study (McLaughlin 2002). Samples were taken from basins 6 and 7, then polymer was input into basin 7 at an estimated dose of 1 mg/L. All samples for each hour were taken at the same time. The results can be seen in Figures 4.2 and 4.3. A significant change was noted in the inlet flow of basin 7 before the third hour. However, no effect was seen in the outflow. Visually, the polymer had no affect on the basin water quality. Basin 6 had very clean input from the recently paved road with very low TSS (<25 mg/L). Very little settling occurred in the basin, with

TSS at the clothed pipe being slightly higher than the input. Overall, the polymer did not demonstrate a significant effect on the settling in basin 7.

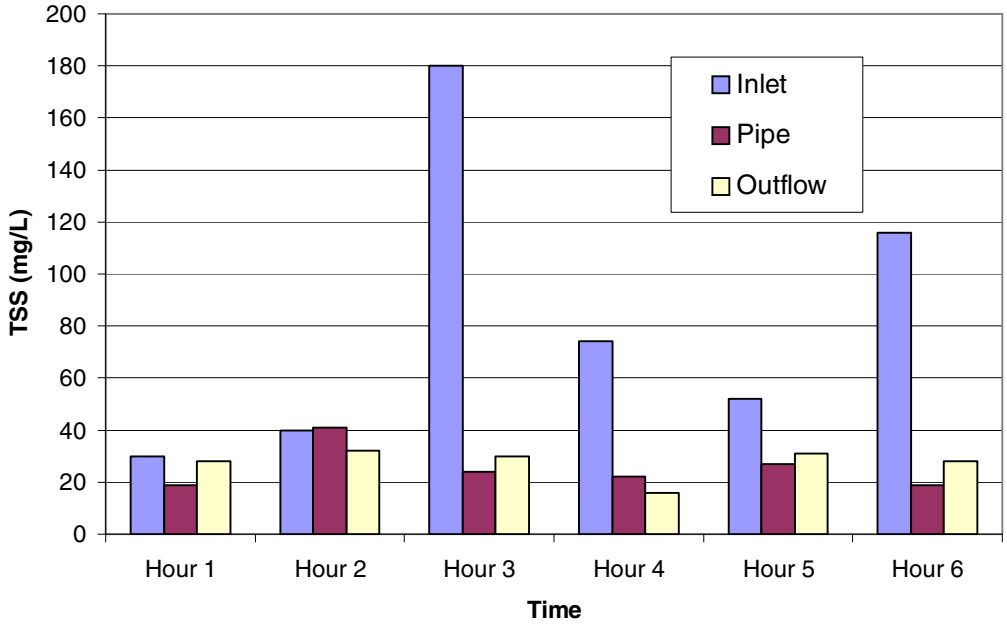

Figure 4.2. TSS data from Basin 7 Field Test June 3, 2005 with A-100 addition, 1 mg/L. All samples for each hr taken at same time and values within a single time should not be used to estimate settling efficiency.

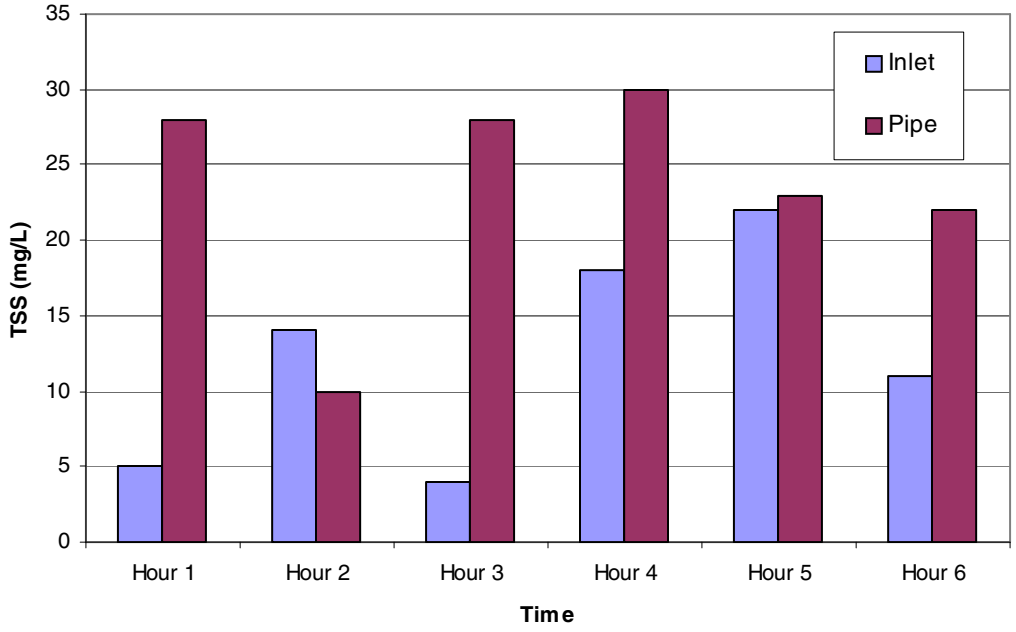

Figure 4.3. TSS data from Basin 6 Field Test June 3, 2005 without polymer

4.2. Laboratory Tests

These laboratory tests were used to assess the efficiency of coagulants at removing sediment in stormwater. Each coagulant was tested at several doses to determine the optimum dose for that coagulant in the stormwater present at the MD 43 construction site.

The first samples taken in laboratory studies were tested only for TSS. Through these experiments, it became apparent that TSS was not the proper measurement for these particular stormwater ponds. Many of the sediment particles were passing through the 1 μm filter into the effluent. Upon adding

the polymer, these particles would flocculate, but not settle. The subsequent TSS measurement indicated that TSS had increased with settling time because the agglomerated small particles now did not pass through the TSS filter. With the addition of a TDS measurement and plotting of Total Solids (TS), the samples could be normalized to compensate for the small particles. Since dissolved solids are changed insignificantly by the polymer addition, the TS chart best represents the suspended solids present in the samples.

The nonionic polyacrylamide N-300 was tested at various concentrations with stormwater from basin 9 collected on June 28, 2005. After 24 hours of settling, there were negligible differences between the use of the polymer and no polymer in TS and TSS measurements (Figures 4.4 and 4.5). After 24 hours, the turbidity also showed no significant difference between samples (Figure 4.6).

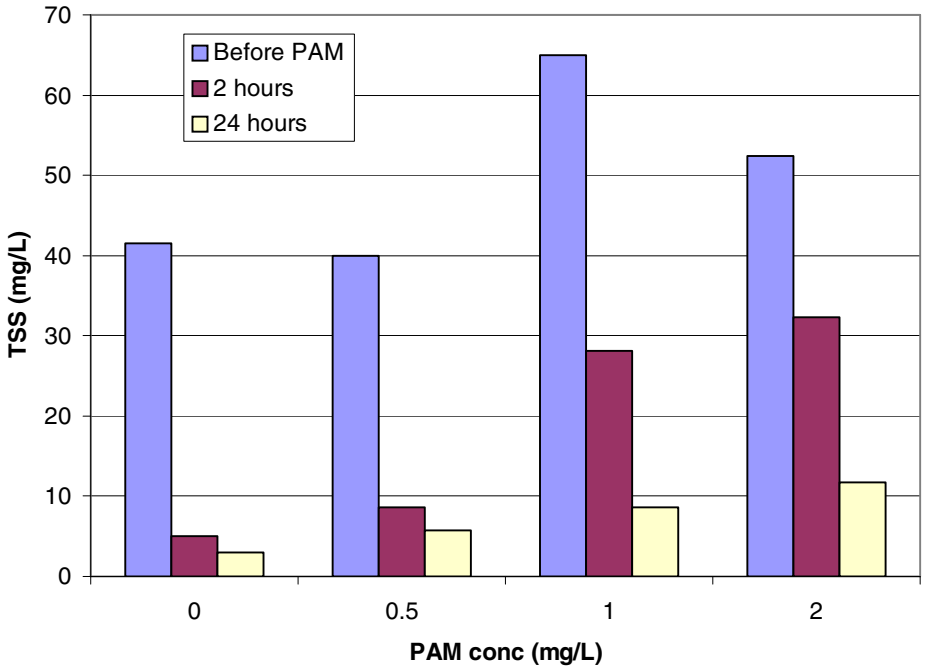

Figure 4.4. TSS data with N-300 Lab Test Basin 9 collected June 28, 2005

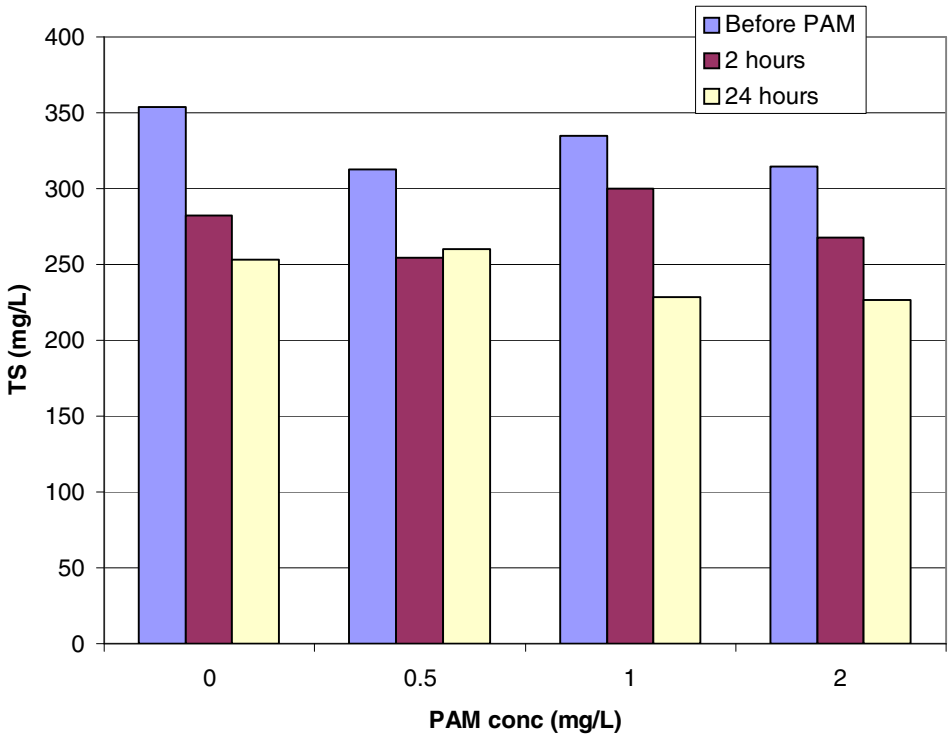

Figure 4.5. TS data with N-300 Lab Test Basin 9 collected June 28, 2005

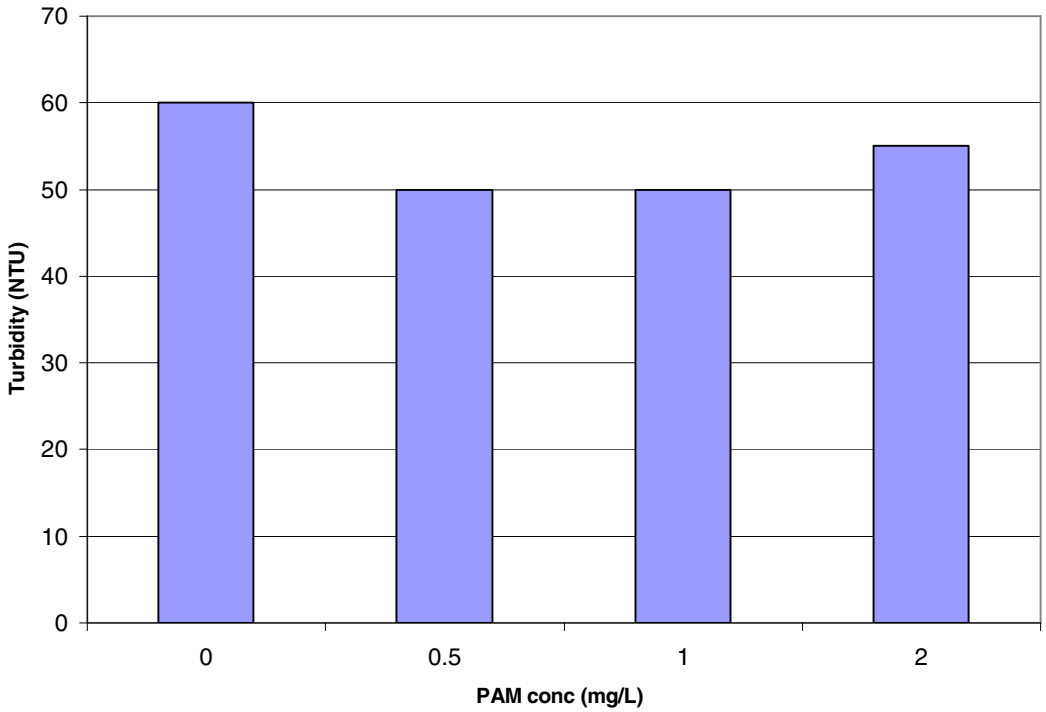

Figure 4.6. Turbidity after 24 hours with N-300 Lab Test Basin 9 collected June 28, 2005

The anionic polyacrylamide A-110 was tested with stormwater from basin 9 collected on June 28, 2005. After 24 hours of settling, a slight decrease in TS (although not in TSS) was noted with polymer use (Figures 4.7 and 4.8). However, this difference was not noticed in the turbidity measurement (Figure 4.9).

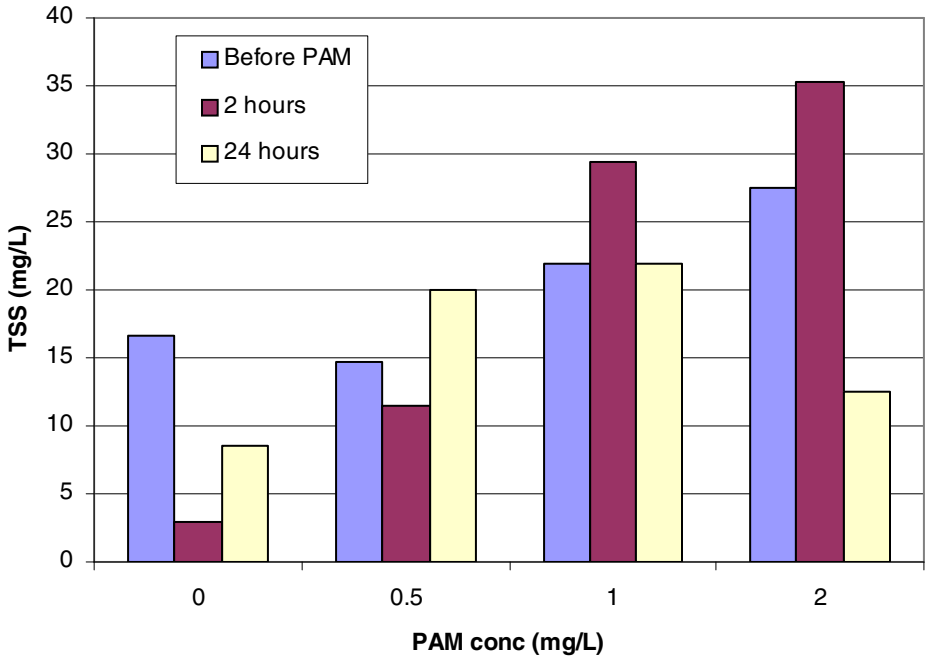

Figure 4.7. TSS data with A-110 Lab Test Basin 9 collected June 28, 2005

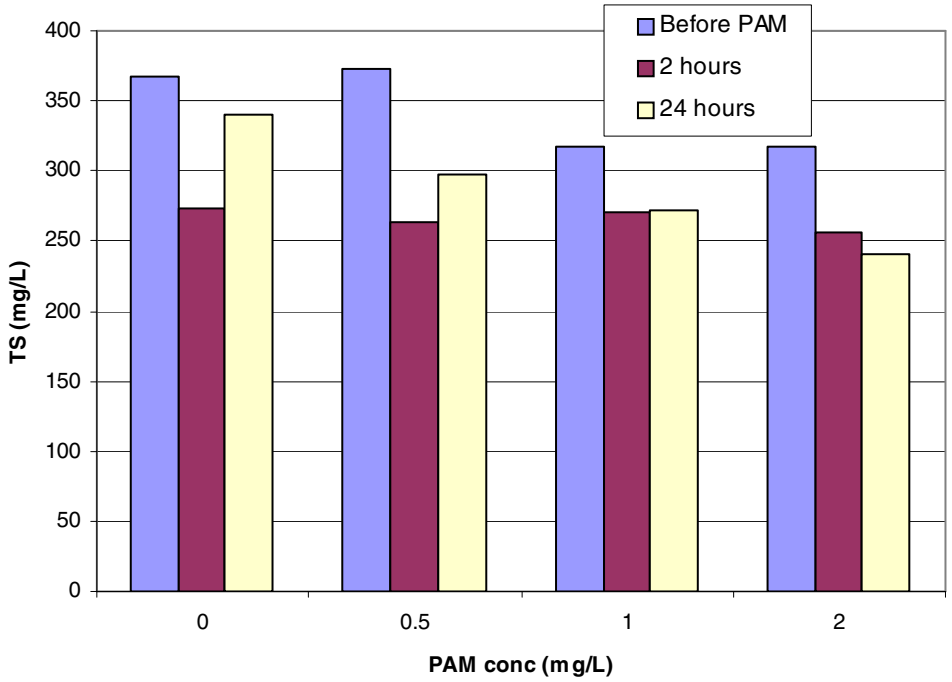

Figure 4.8. TS data with A-110 Lab Test Basin 9 collected June 28, 2005

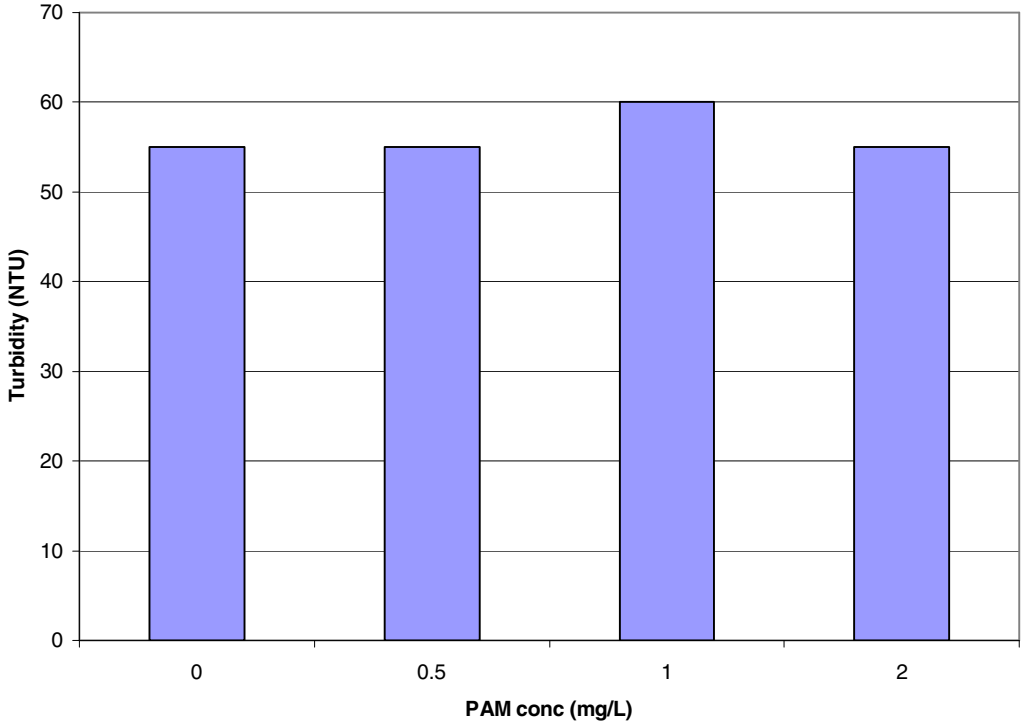

Figure 4.9. Turbidity after 24 hours with A-110 Lab Test Basin 9 collected June 28, 2005

Anionic polyacrylamide A-120 and A-100 were tested with stormwater from basin 8 collected on July 5, 2005. The runoff sediment on this date was very sandy and significant settling was observed in all samples. In both cases no difference was noticed in the settling with or without polymer after 2 hours or after 24 hours (Figures 4.10 and 4.11, Figures 4.13 and 4.14). For A-120, the turbidity difference was negligible as well (Figure 4.12). For A-100, the measured turbidity for the sample without polymer was higher than the samples with polymer, but the visual difference was negligible with turbidity values below 10 NTUs (Figure 4.15).

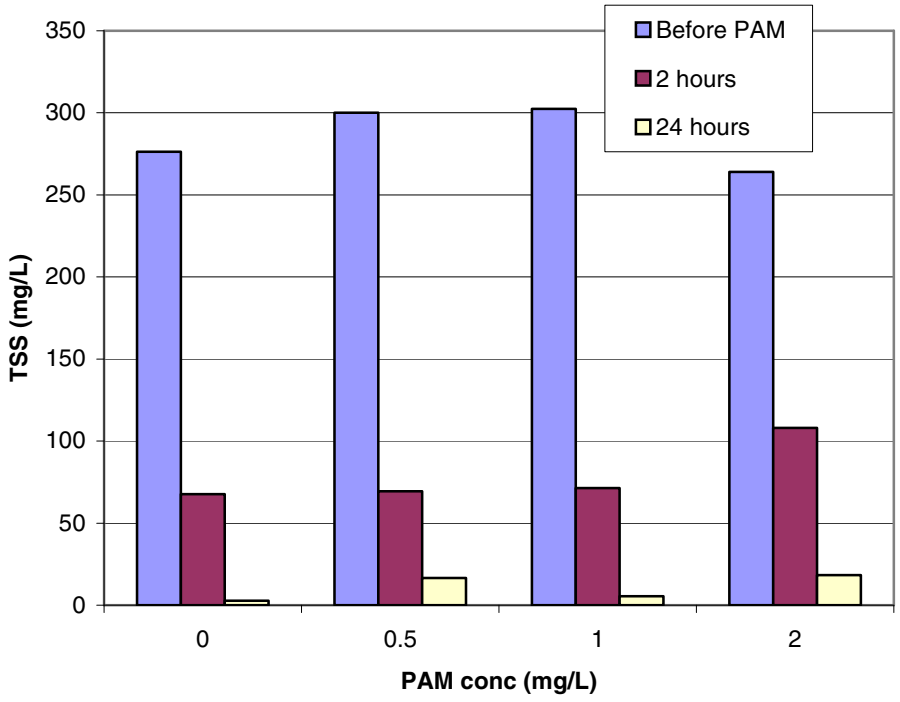

Figure 4.10. TSS data with A-120 Lab Test Basin 8 collected July 5, 2005

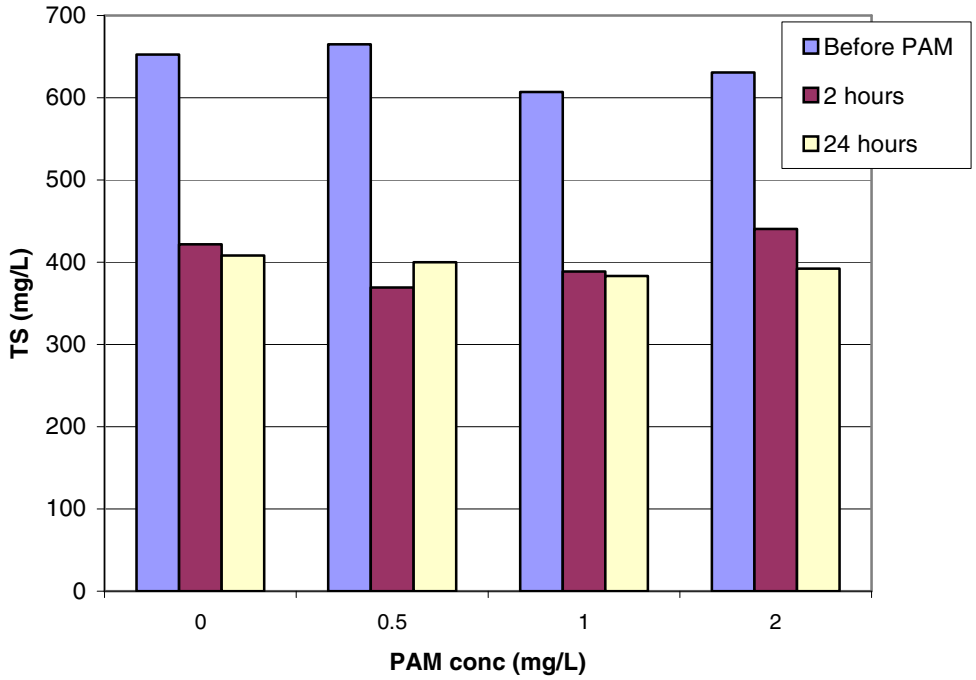

Figure 4.11. TS data with A-120 Lab Test Basin 8 collected July 5, 2005

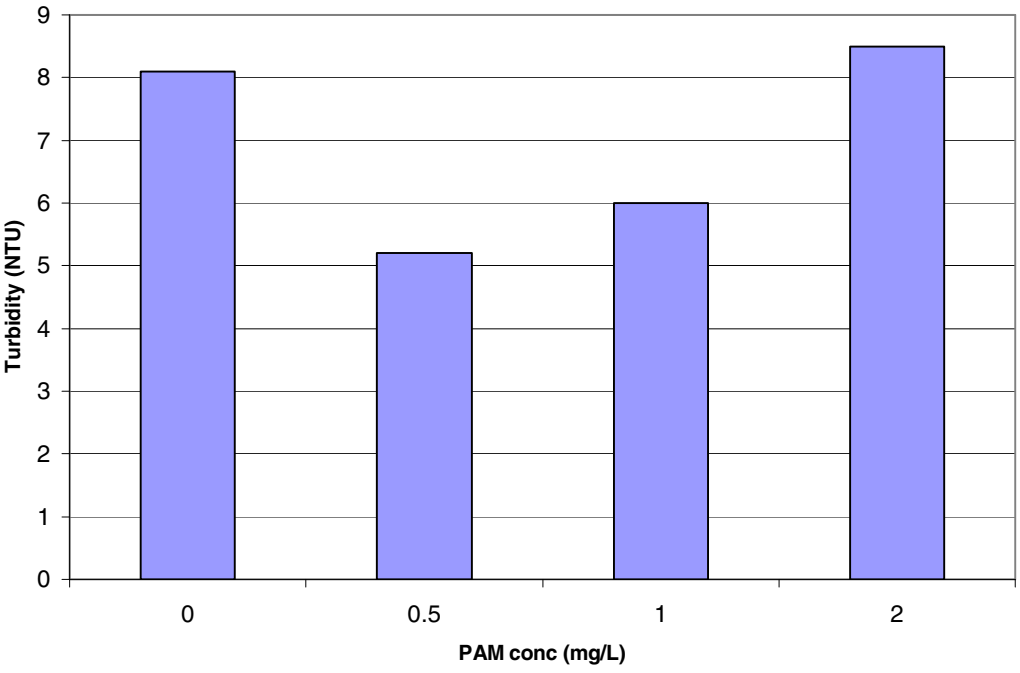

Figure 4.12. Turbidity after 24 hours with A-120 Lab Test Basin 8 collected July 5, 2005

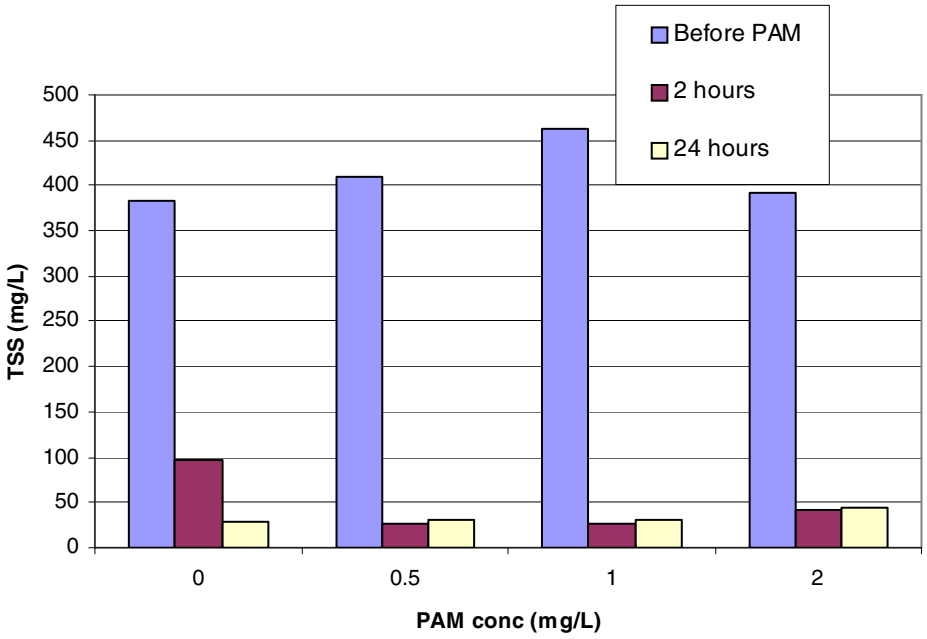

Figure 4.13. TSS data with A-100 Lab Test Basin 8 collected July 5, 2005

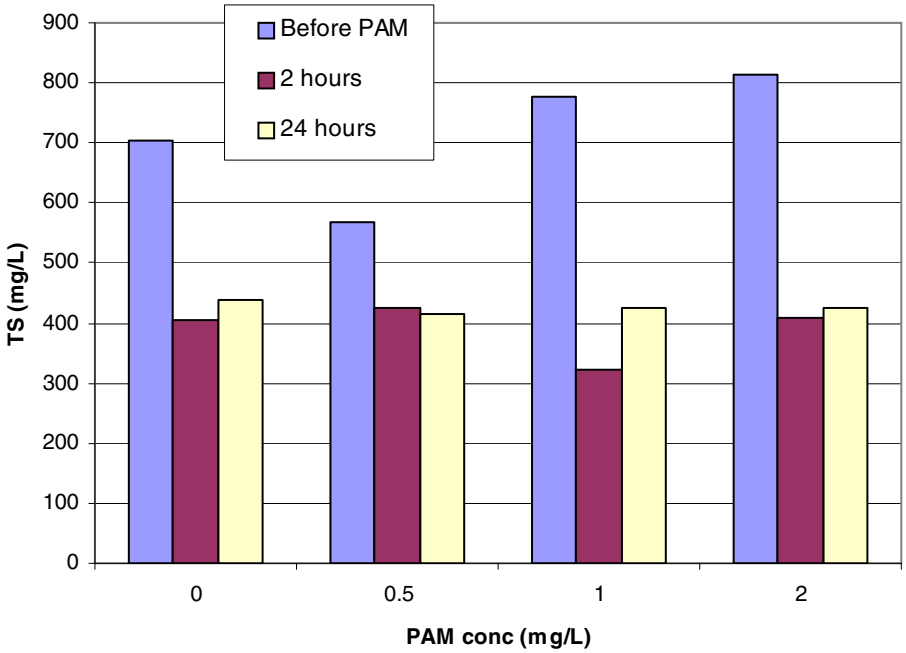

Figure 4.14. TS data with A-100 Lab Test Basin 8 collected July 5, 2005

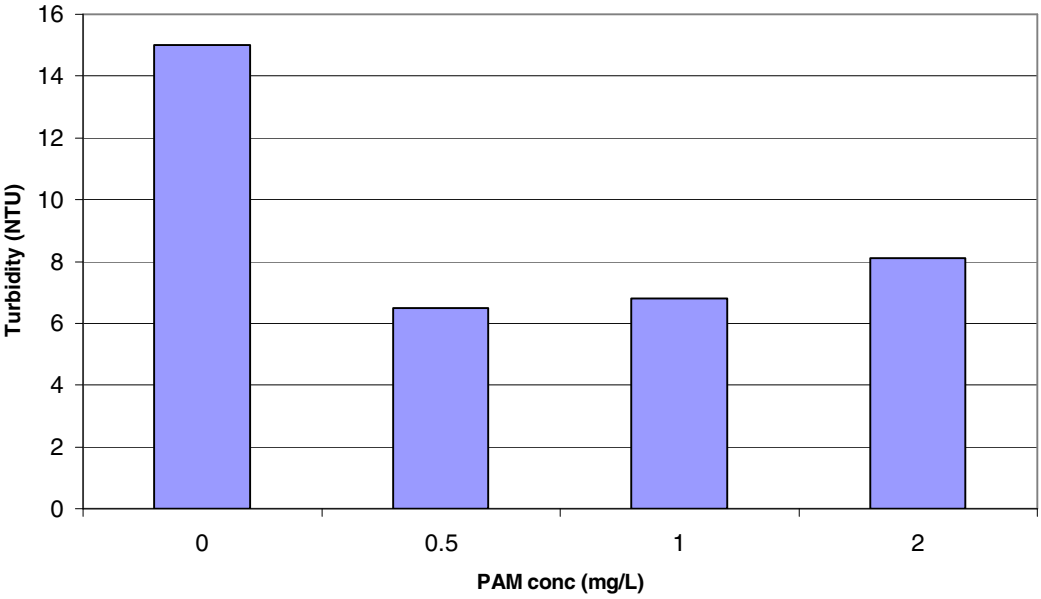

Figure 4.15. Turbidity after 24 hours with A-100 Lab Test Basin 8 collected July 5, 2005

Anionic polyacrylamide A-130 and A-150 were tested with stormwater from basin 9 collected on July 20, 2005. A slight increase in settling efficiency was noticed in the TS measurement for A-130 concentrations of 0.5 and 1.0 mg/L (Figures 4.16 and 4.17). However, the turbidity data did not reflect this difference (Figure 4.18). For A-150, a slight decrease in TS concentration corresponded with an increase of polymer concentration (Figures 4.19 and 4.20). Again, this difference was not manifested in the turbidity measurements (Figure 4.21).

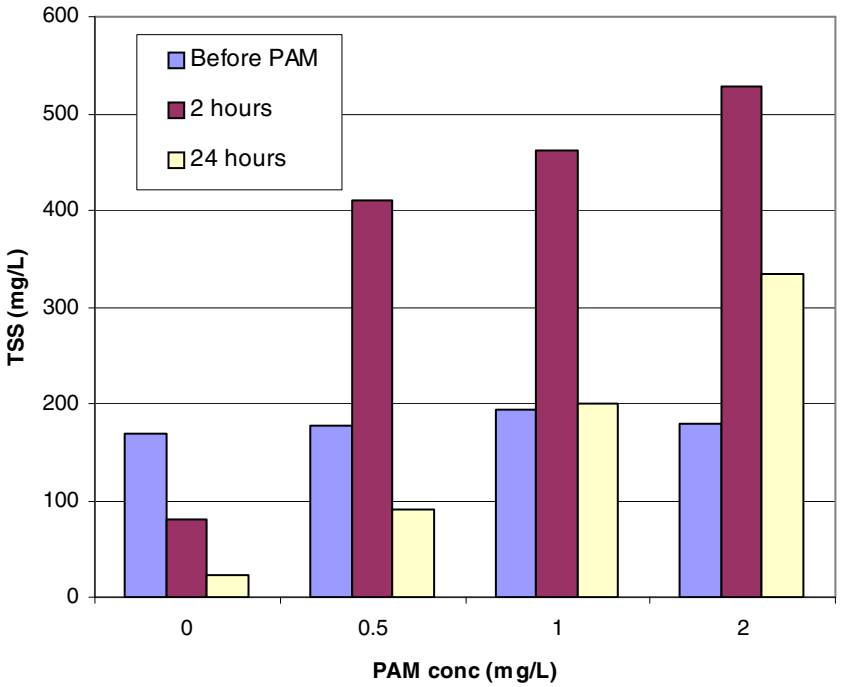

Figure 4.16. TSS data with A-130 Lab Test Basin 9 collected July 20, 2005

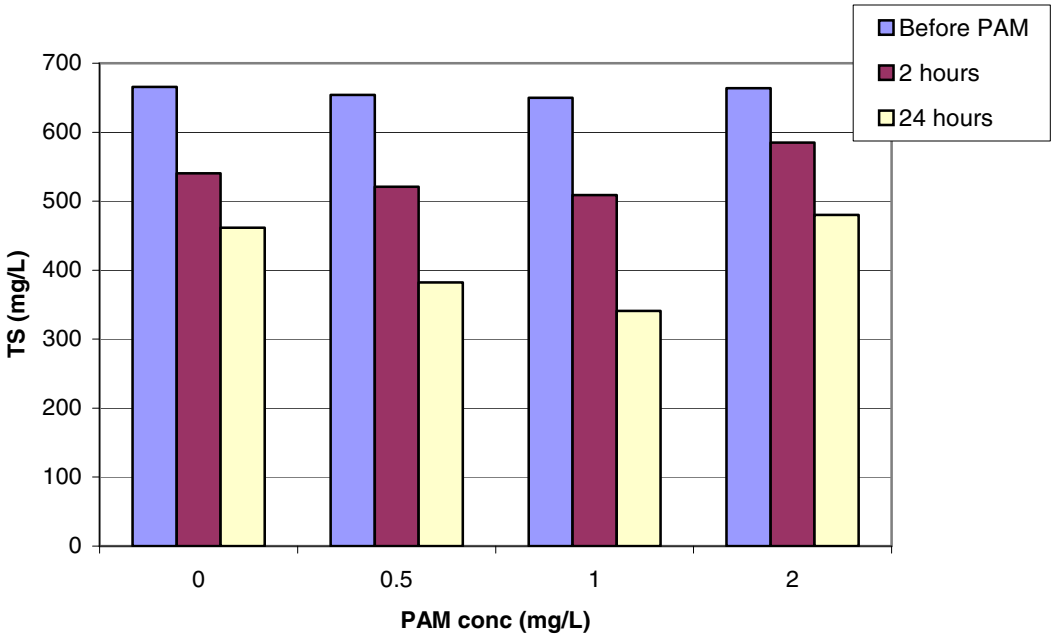

Figure 4.17. TS data with A-130 Lab Test Basin 9 collected July 20, 2005

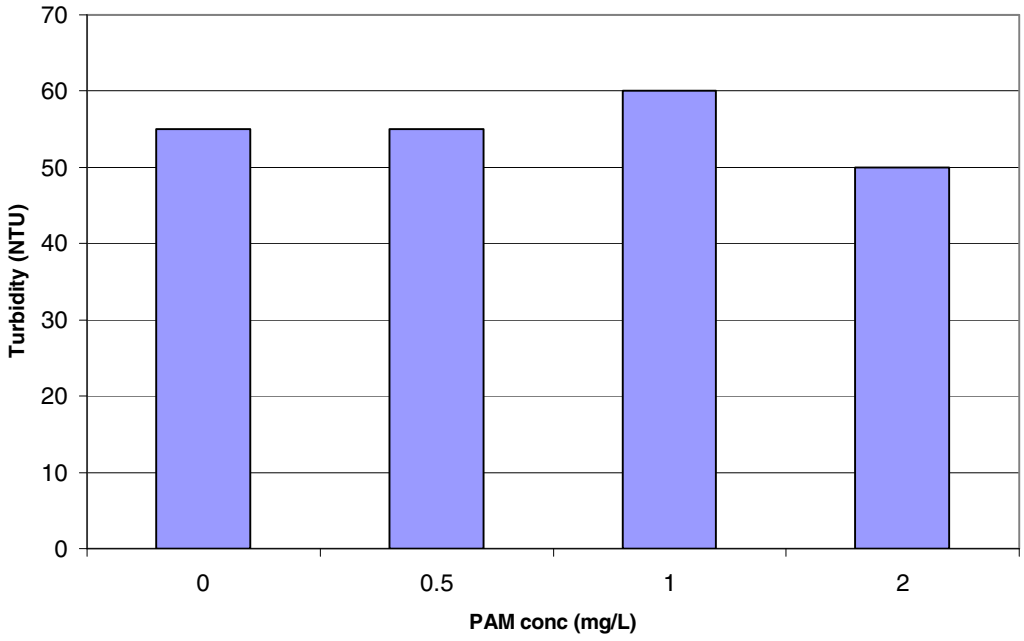

Figure 4.18. Turbidity after 24 hours with A-130 Lab Test Basin 9 collected July 20, 2005

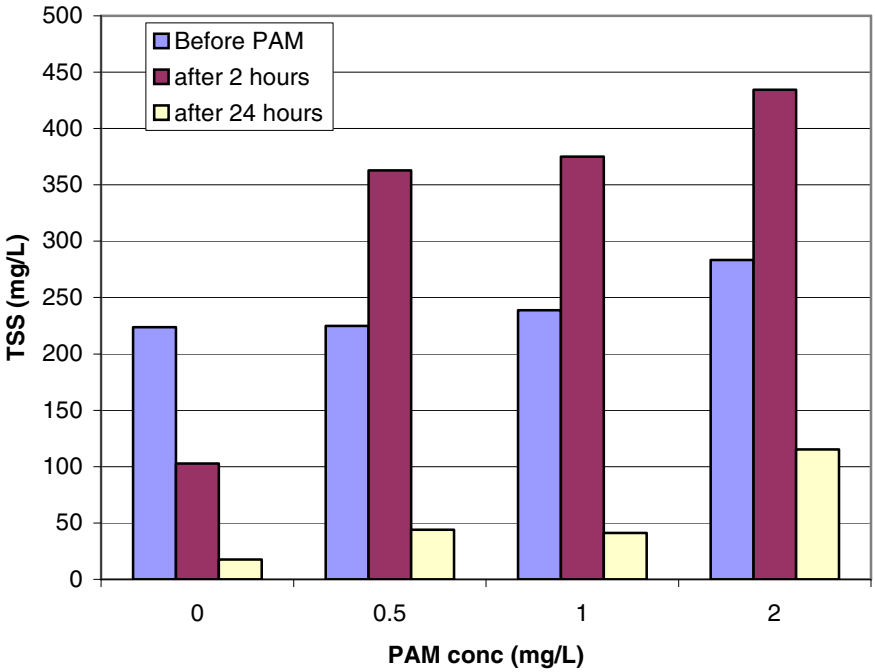

Figure 4.19. TSS data with A-150 Lab Test Basin 9 collected July 20, 2005

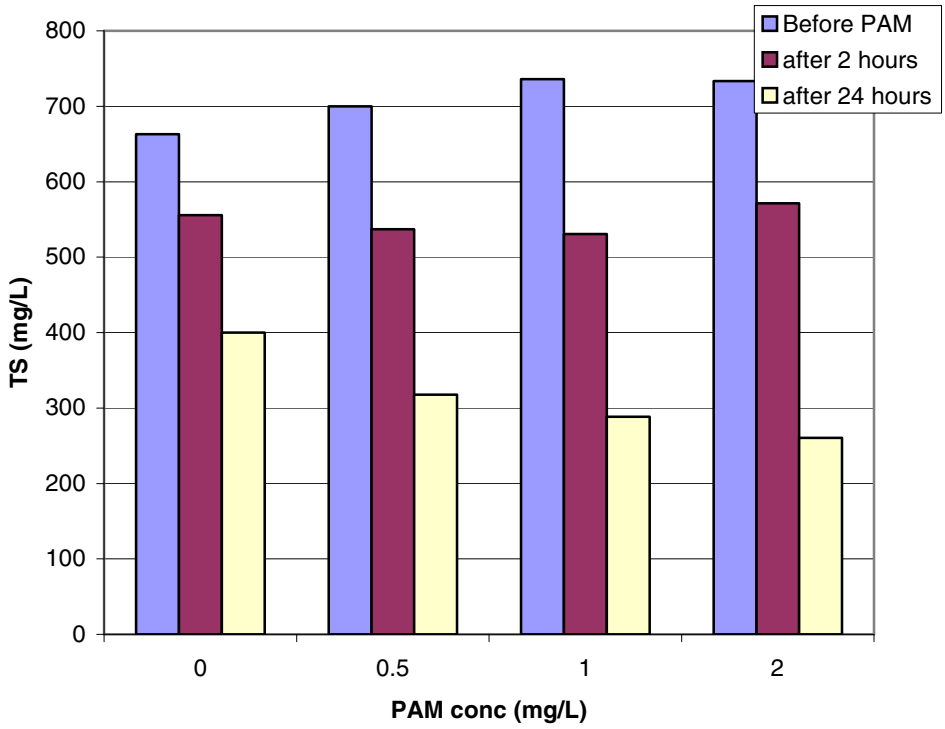

Figure 4.20. TS data with A-150 Lab Test Basin 9 collected July 20, 2005

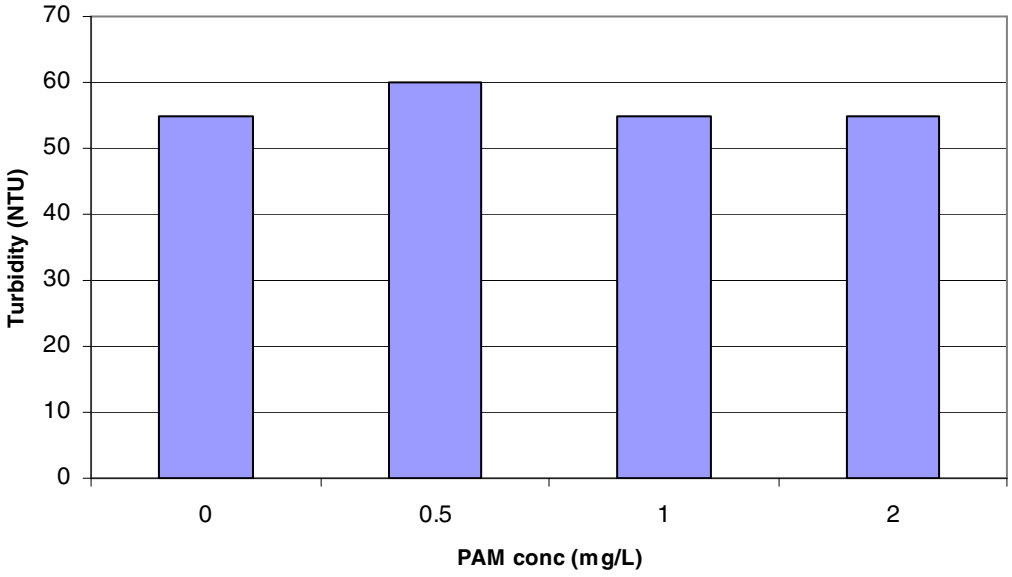

Figure 4.21. Turbidity after 24 hours with A-150 Lab Test Basin 9 collected July 20, 2005

The polymer Superfloc A-150 was retested at high concentrations because of the promising TS results at a dose of 2 mg/L (Figure 4.20). Stormwater collected from basin 9 on October 10, 2005 was tested with doses of 0, 2, 4, 6, 8, and 10 mg/L. A dose of 2 mg/L demonstrated a decrease in TS and turbidity (Figure 4.23 and 4.24). However, the TS and turbidity increased with higher doses of polyacrylamide. A dose of 2 mg/L is likely the optimum dose of A-150 for the sediment (Figures 4.22-4.24).

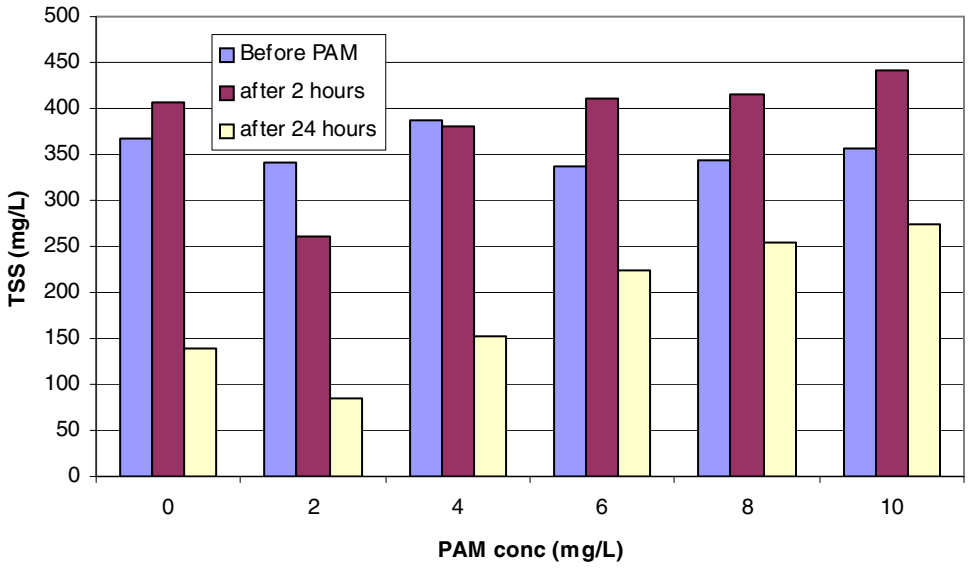

Figure 4.22. TSS data with A-150 Lab Test Basin 9 collected October 10, 2005

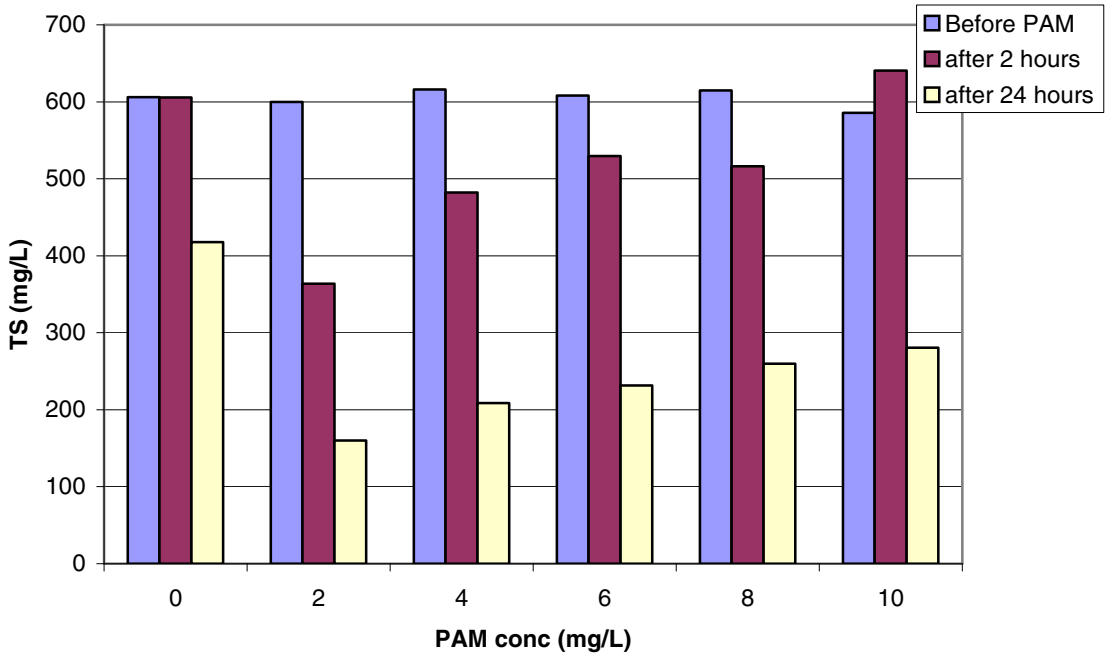

Figure 4.23. TS data with A-150 Lab Test Basin 9 collected October 10, 2005

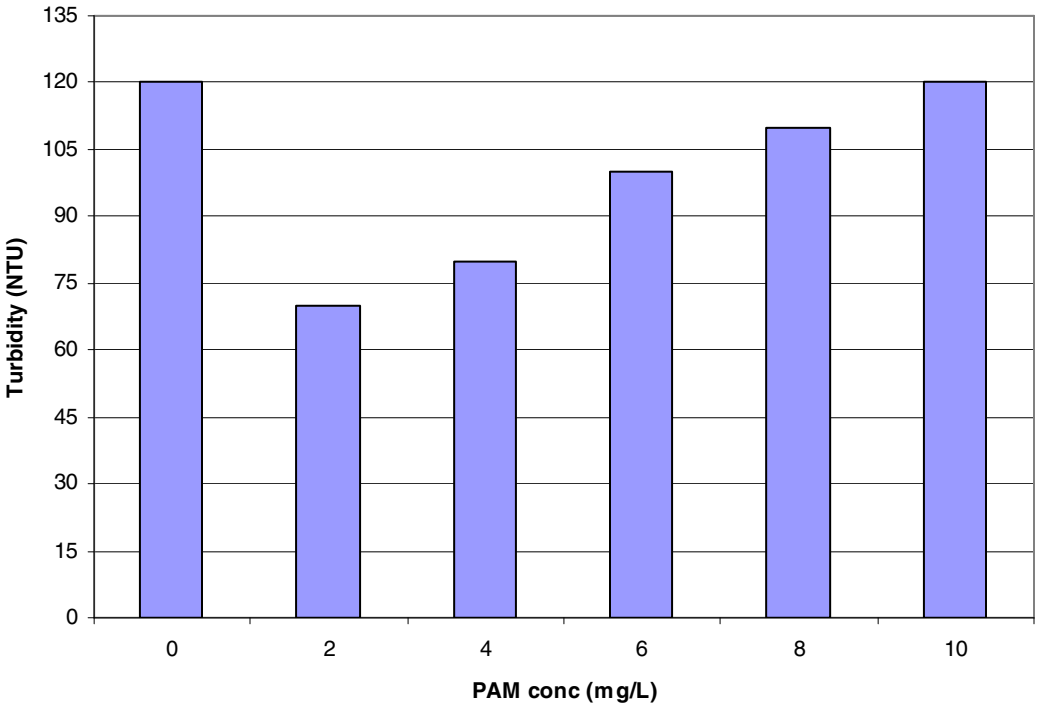

Figure 4.24. Turbidity data with A-150 Lab Test Basin 9 collected October 10, 2005

Two tests were performed with alum using doses of 0, 20, 40, 60, 80, and 100 mg/L (Figures 4.25 and 4.28). Stormwater collected on October 10, 2005 from basin 9 had high initial TS of about 600 mg/L, while stormwater collected from basin 8 on October 22, 2005 had low initial TS of about 175 mg/L (Figures 4.26 and 4.29). Both tests displayed similar results for TS and turbidity (Figures 4.27 and 4.30). A steady decrease in TS and turbidity corresponded with an increase in alum dosage, indicating effective coagulation/flocculation. A more significant decrease in TS and turbidity was noted after 40 mg/L with very low turbidities noted at 80 and 100 mg/L, 5 NTU and 4 NTU, respectively (Figure 4.30). Thus, alum showed promise as a potential coagulant for field testing.

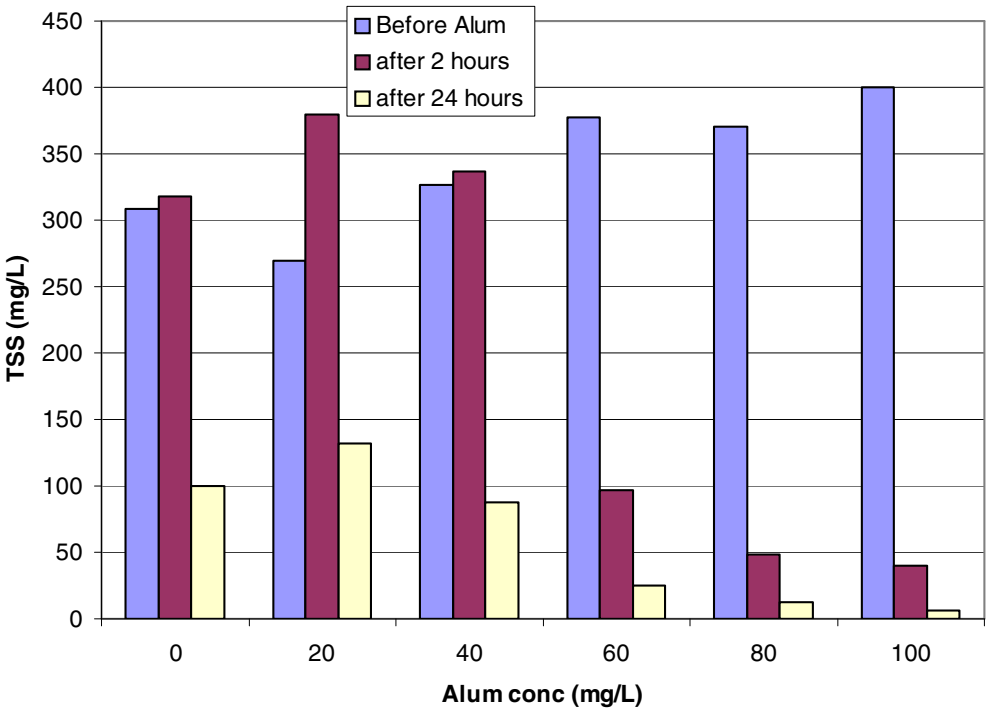

Figure 4.25. TSS data with Alum Lab Test Basin 9 collected October 10, 2005

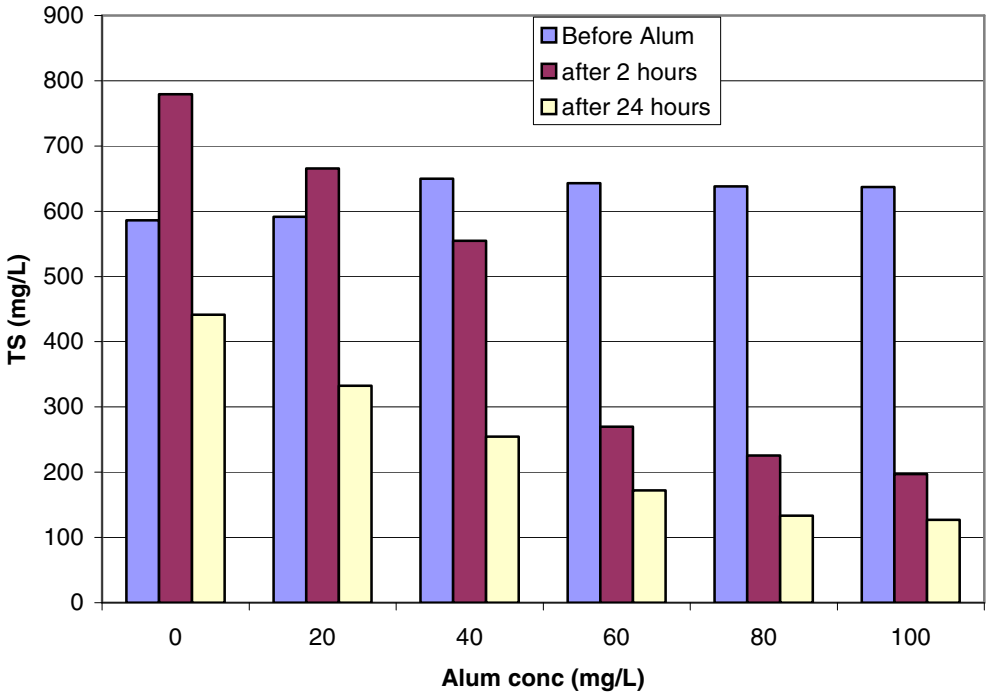

Figure 4.26. TS data with Alum Lab Test Basin 9 collected October 10, 2005

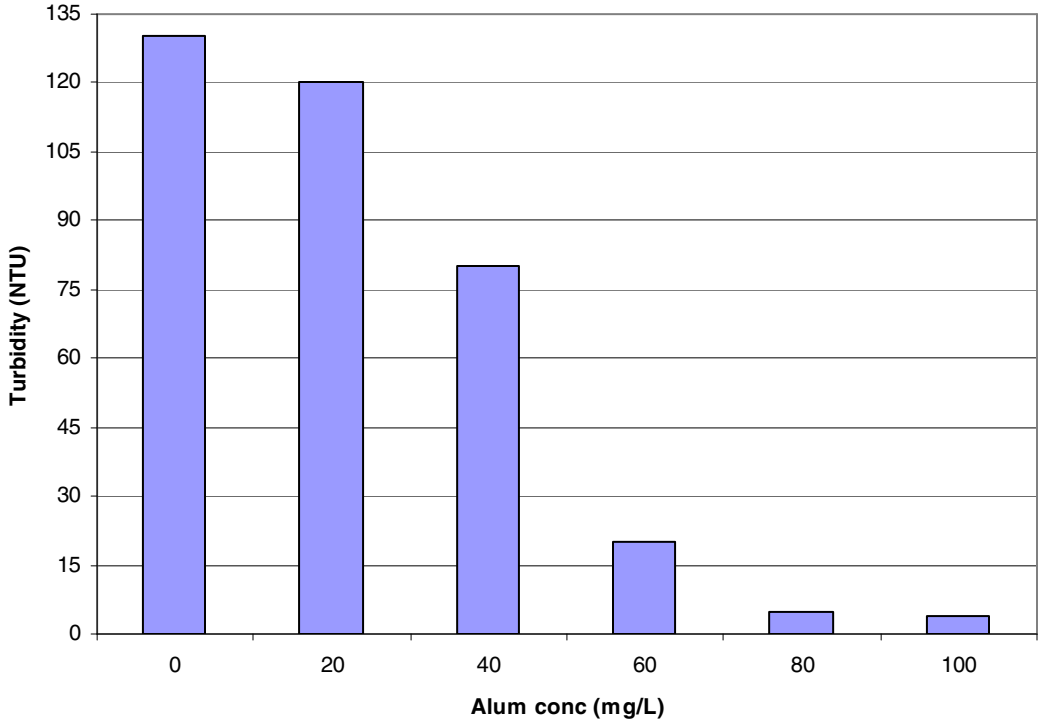

Figure 4.27. Turbidity after 24 hours with Alum Lab Test Basin 9 collected October 10, 2005

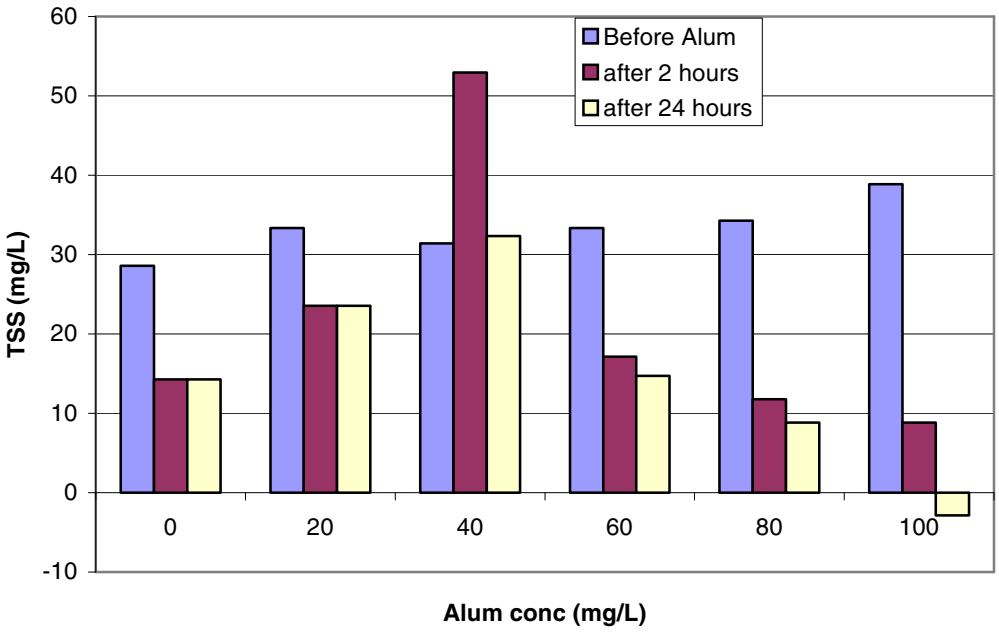

Figure 4.28. TSS data with Alum Lab Test Basin 8 collected October 22, 2005

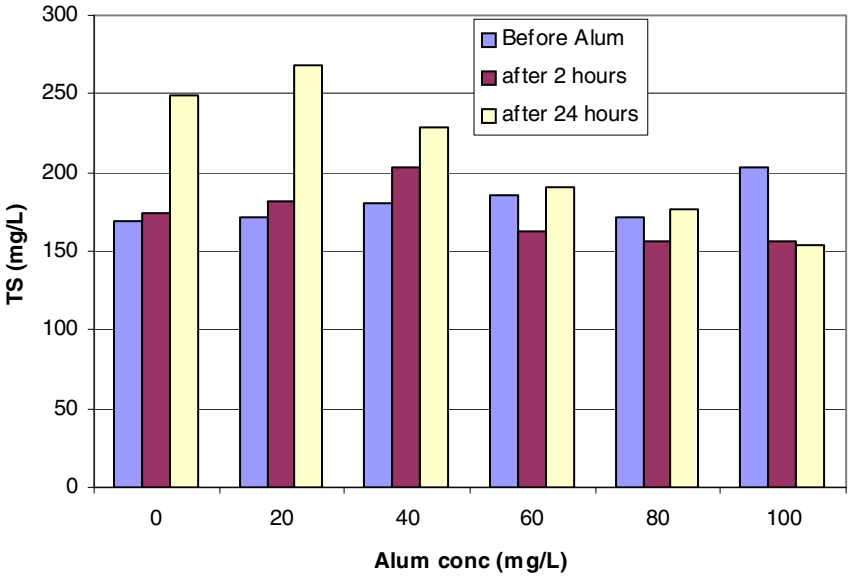

Figure 4.29. TS data with Alum Lab Test Basin 8 collected October 22, 2005

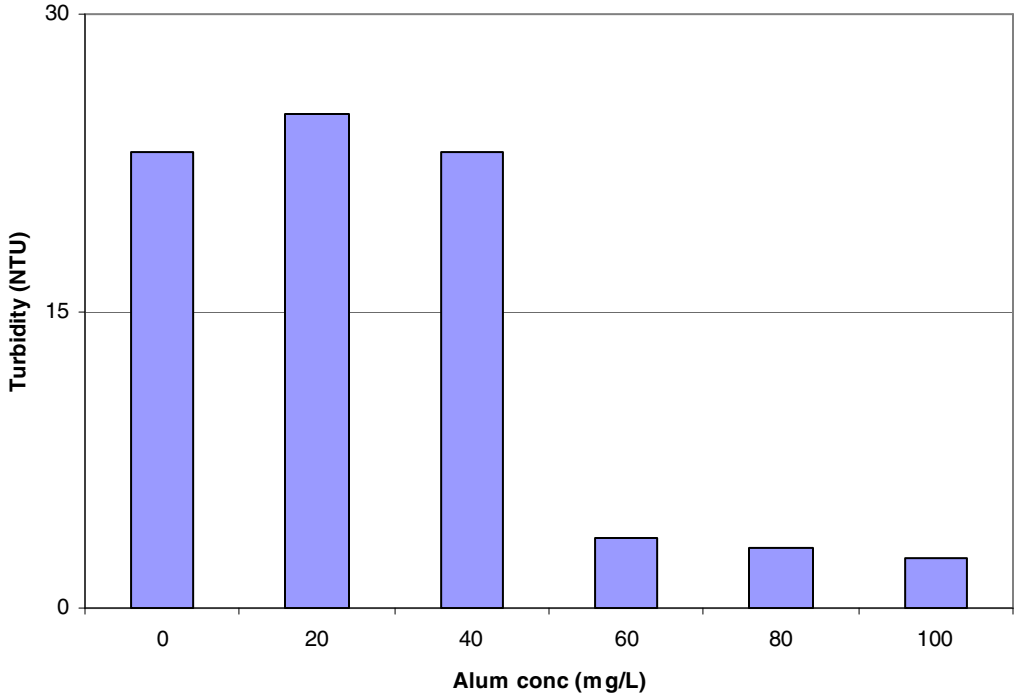

Figure 4.30. Turbidity after 24 hours with Alum Lab Test Basin 8 collected October 22, 2005

The polymer Superfloc A-130V was tested because it had an "ultra high" molecular weight. Stormwater collected from basin 9 on November 23, 2005 was high in TS, about 550 mg/L and low in TSS, about 60 mg/L (Figures 4.31 and 4.32). A comparison of the lab trials illustrate that A-130V had little effect on TSS, TS, or turbidity (Figures 4.31, 4.32, and 4.33). Though the differences are slight, the sample with no coagulant had the greatest removal of TSS, while the sample with 10 mg/L of A-130V had the greatest removal of TS. Turbidity values were all small and turbidity reductions were negligible for all doses.

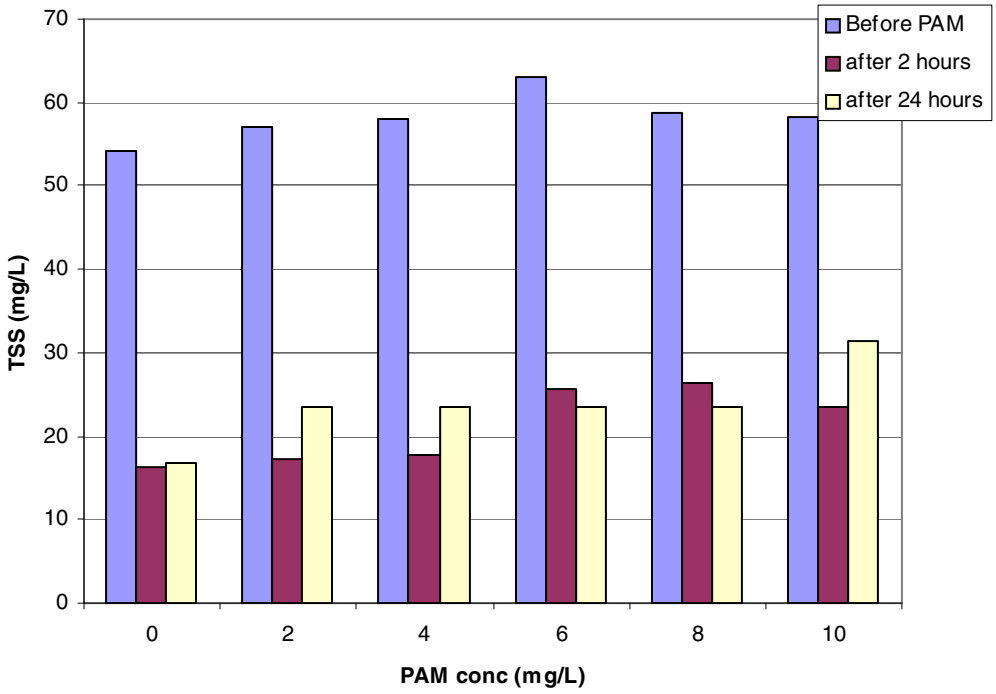

Figure 4.31. TSS data with A-130V Lab Test Basin 6 collected November 23, 2005

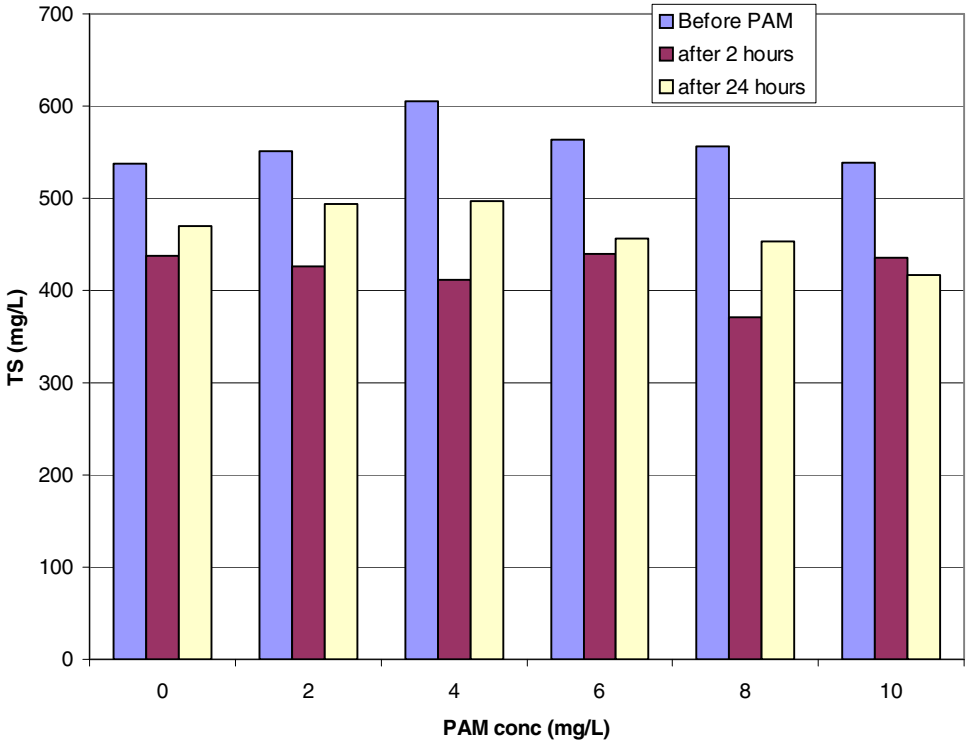

Figure 4.32. TS data with A-130V Lab Test Basin 6 collected November 23, 2005

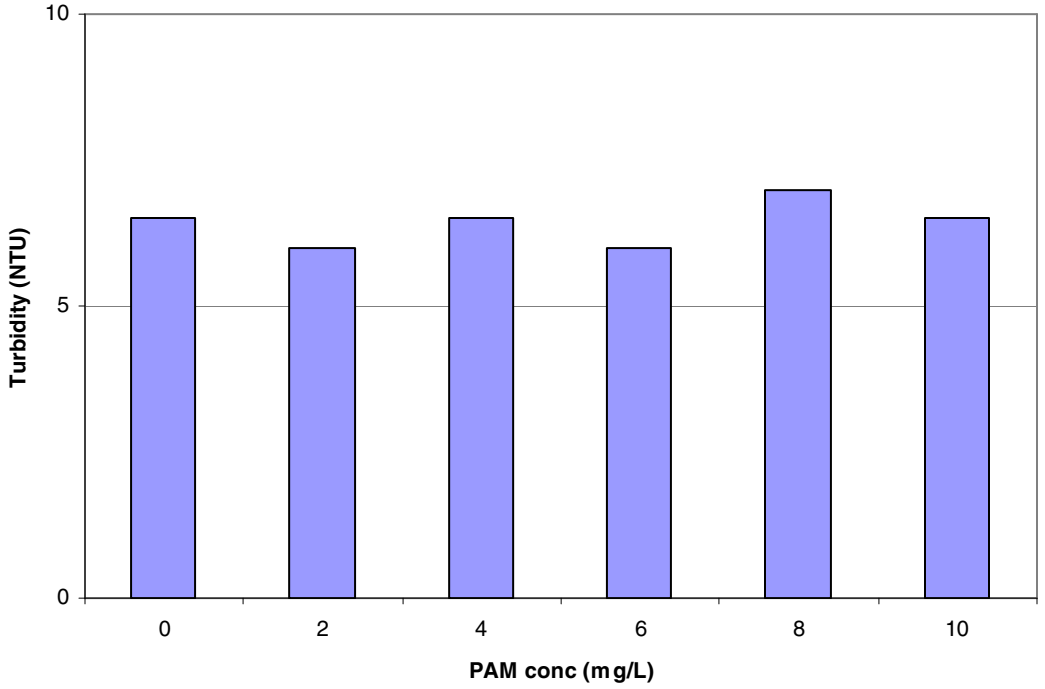

Figure 4.33. Turbidity after 24 hours with A-130V Lab Test Basin 6 collected November 23, 2005

The polymer Superfloc C-446 was tested using stormwater collected from basin 9 on November 23, 2005. These samples had lower TS values than those collected the same day and used in the A-130V trial. At doses of 4 mg/L and higher, C-446 demonstrated significant removal of TSS and TS and lowered turbidity more than no coagulant (Figures 4.34, 4.35, and 4.36). A dose of 8 mg/L appeared to be optimal on all three tests, reducing TSS to <4 mg/L, TS to 169 mg/L and turbidity to 1 NTU.

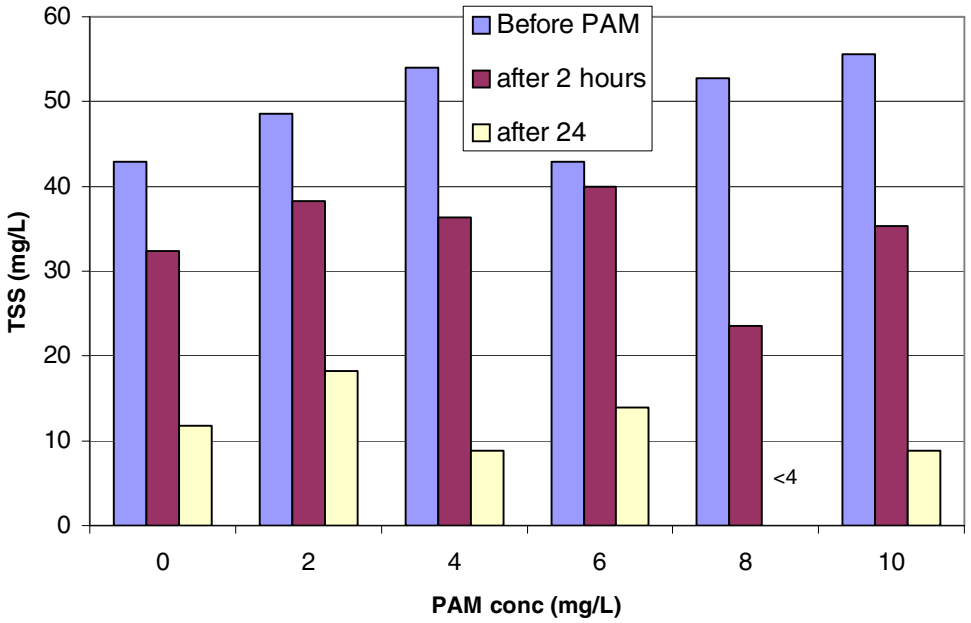

Figure 4.34. TSS data with C-446 Lab Test Basin 9 collected November 23, 2005

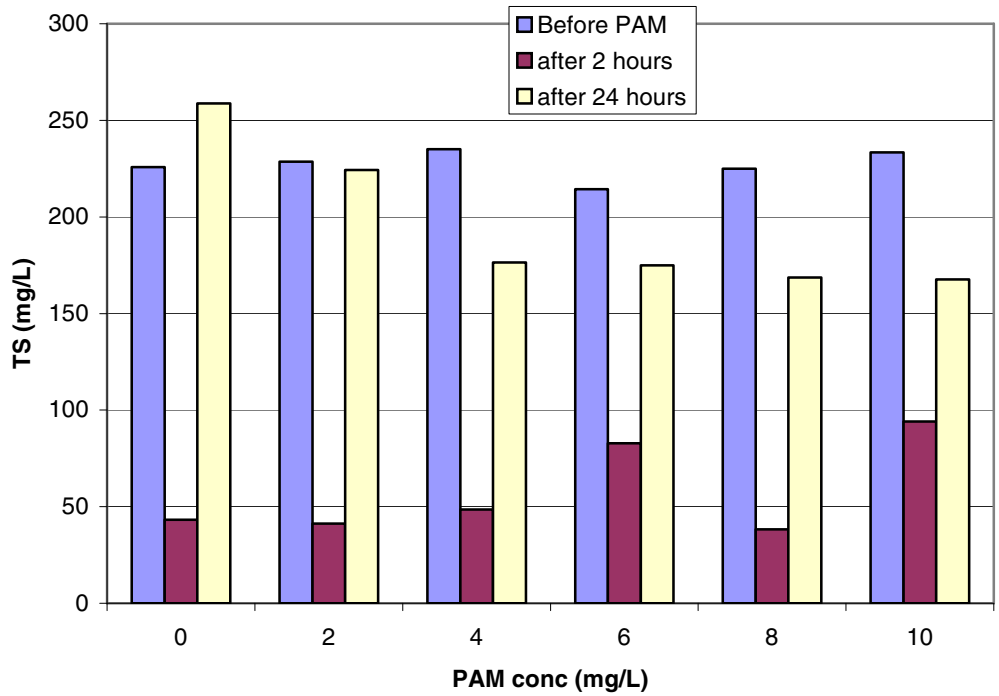

Figure 4.35. TS data with C-446 Lab Test Basin 9 collected November 23, 2005

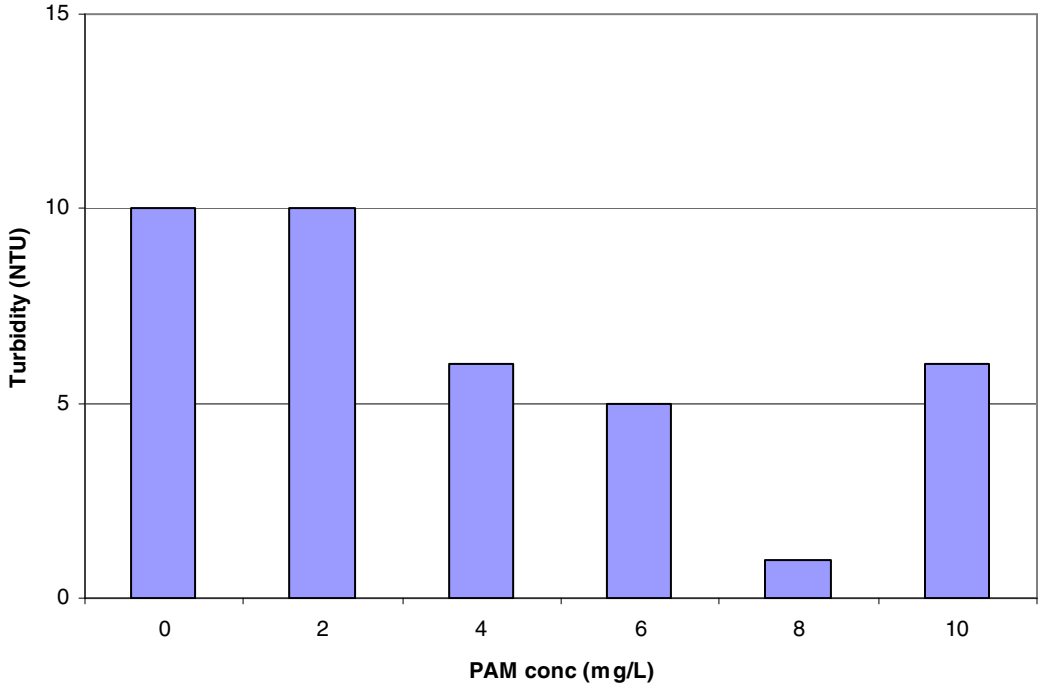

Figure 4.36. Turbidity after 24 hours with C-446 Lab Test Basin 9 collected November 23, 2005

The polymer Superfloc C-496 was tested using stormwater collected from basin 9 on November 23, 2005. These samples were similar in initial measurements to those used in the C-446 trial collected the same day. At a dose of 6 mg/L, the final TSS value was measured to be negative (Figure 4.37). This is likely the result of a low TSS value below the detection limit. Very little collected sediment was noted on the filter. This affects the TS calculation for that dose and gives the false impression that a dose of 6 mg/L removed TS better than it actually did. However, a dose of 6 mg/L still had the best

removal of TSS and TS (Figures 4.37 and 4.38). Turbidity measurements showed minimal differences between the doses (Figure 4.39).

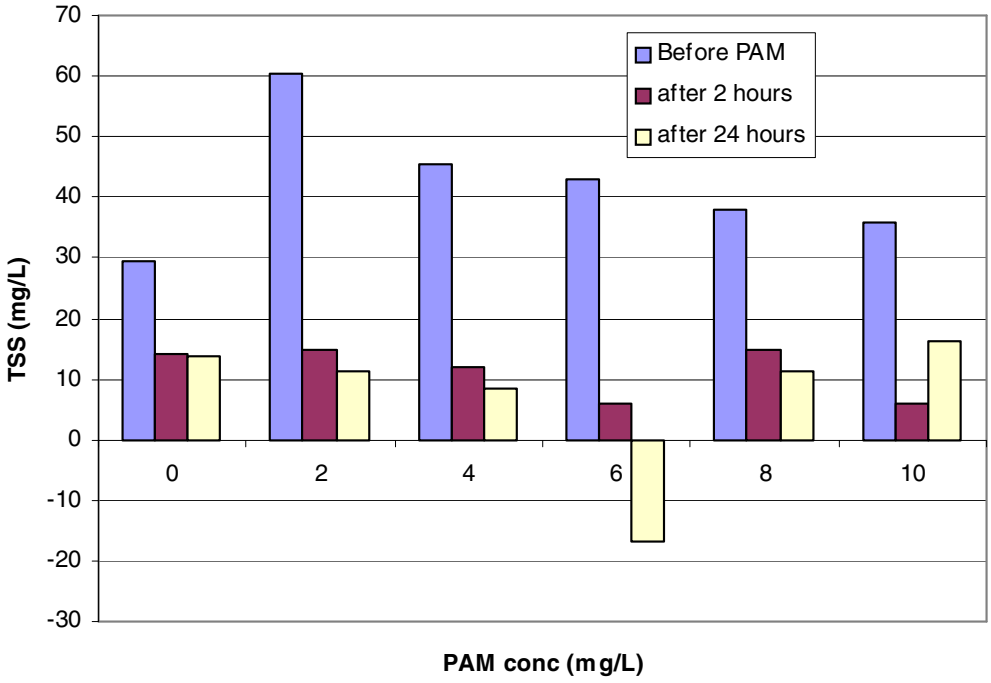

Figure 4.37. TSS data with C-496 Lab Test Basin 9 collected November 23, 2005

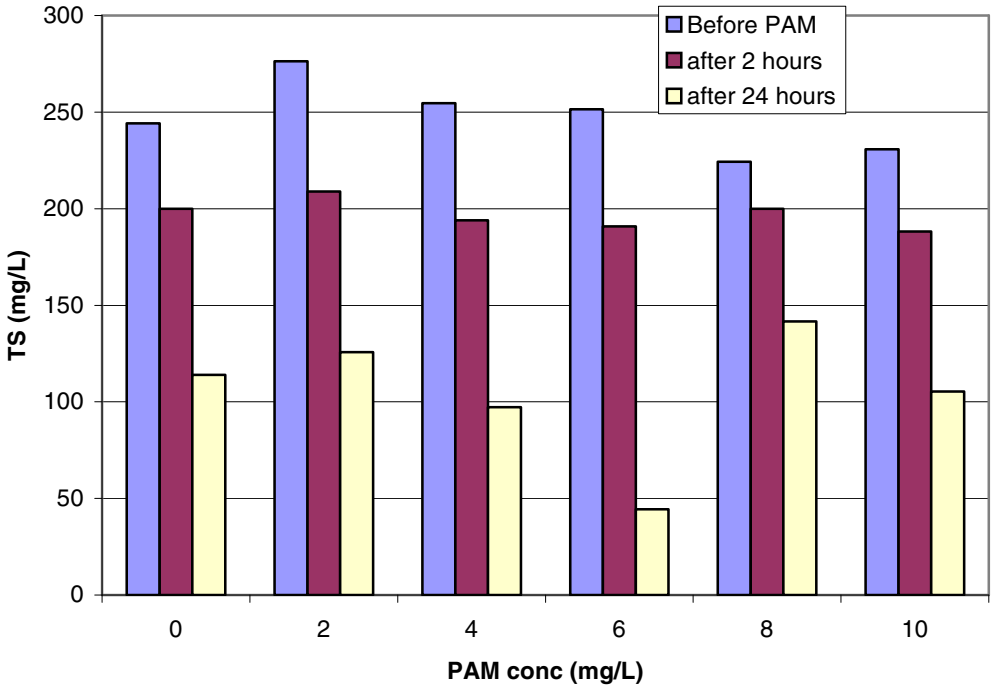

Figure 4.38. TS data with C-496 Lab Test Basin 9 collected November 23, 2005

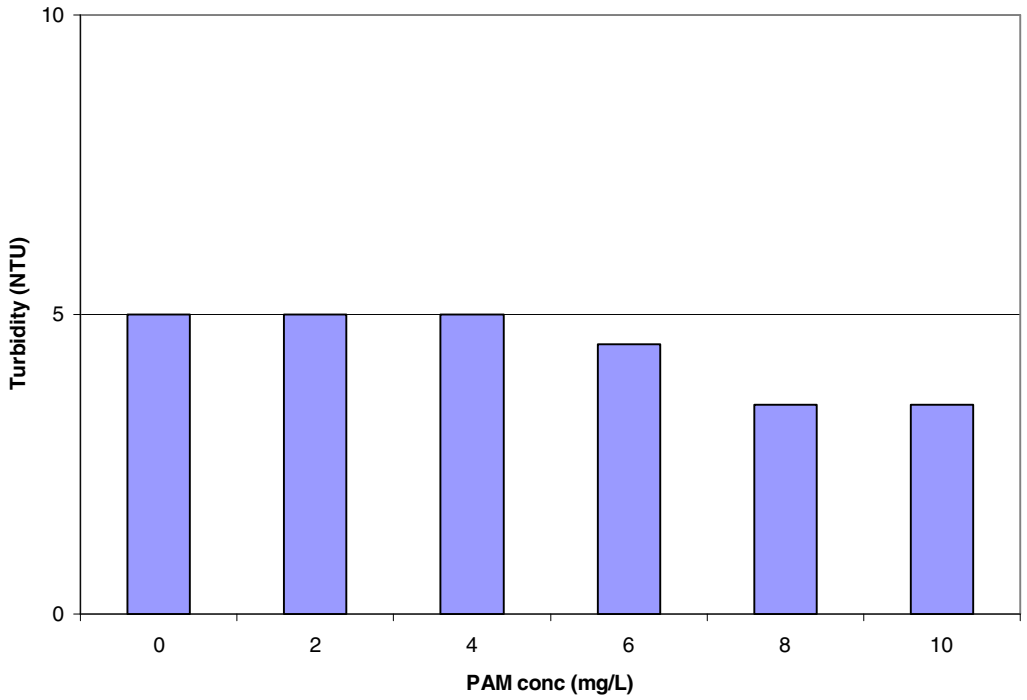

Figure 4.39. Turbidity after 24 hours with C-496 Lab Test Basin 9 collected November 23, 2005

The polymer Superfloc C-448 was tested using stormwater collected from basin 9 on December 19, 2005. A comparison of TSS, TS, and turbidity tests demonstrate that doses of 6 mg/L and higher perform best, with doses of 6 and 8 mg/L performing slightly better than 10 mg/L (Figures 4.40, 4.41, and 4.42). After 24 hours settling, doses 6 and 8 mg/L lowered TSS to 3 mg/L vis-a-vis the 19 mg/L of no coagulant. The turbidity had been reduced to 2 and 3 NTU respectively, while, the water with no coagulant added had a turbidity of 35 NTU.

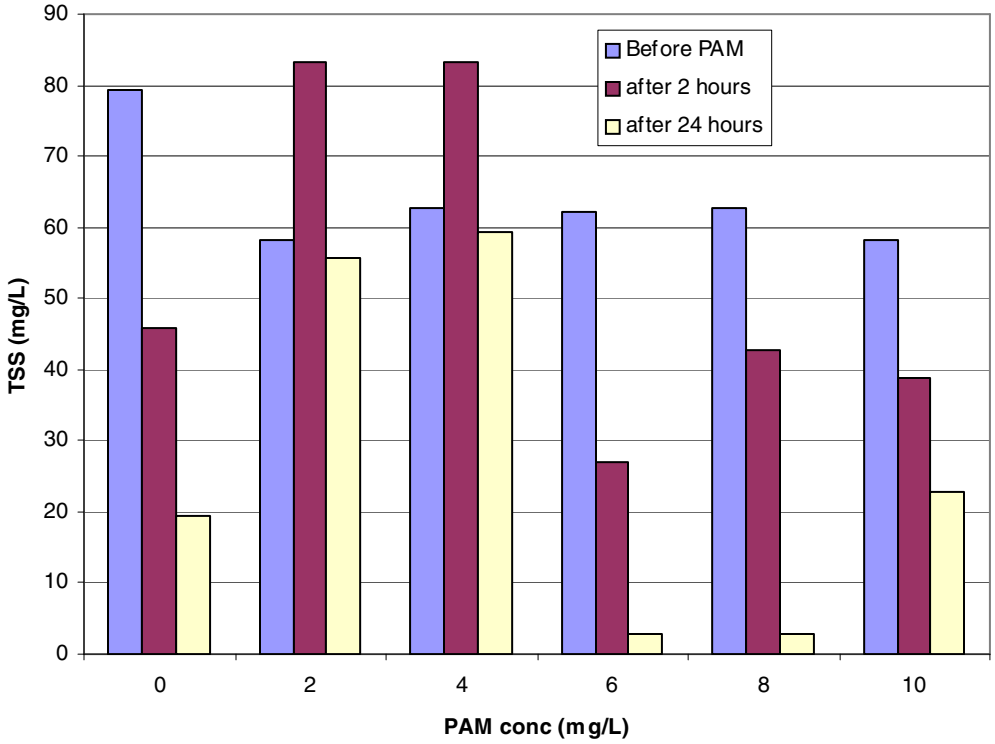

Figure 4.40. TSS data with C-448 Lab Test Basin 9 collected December 19, 2005

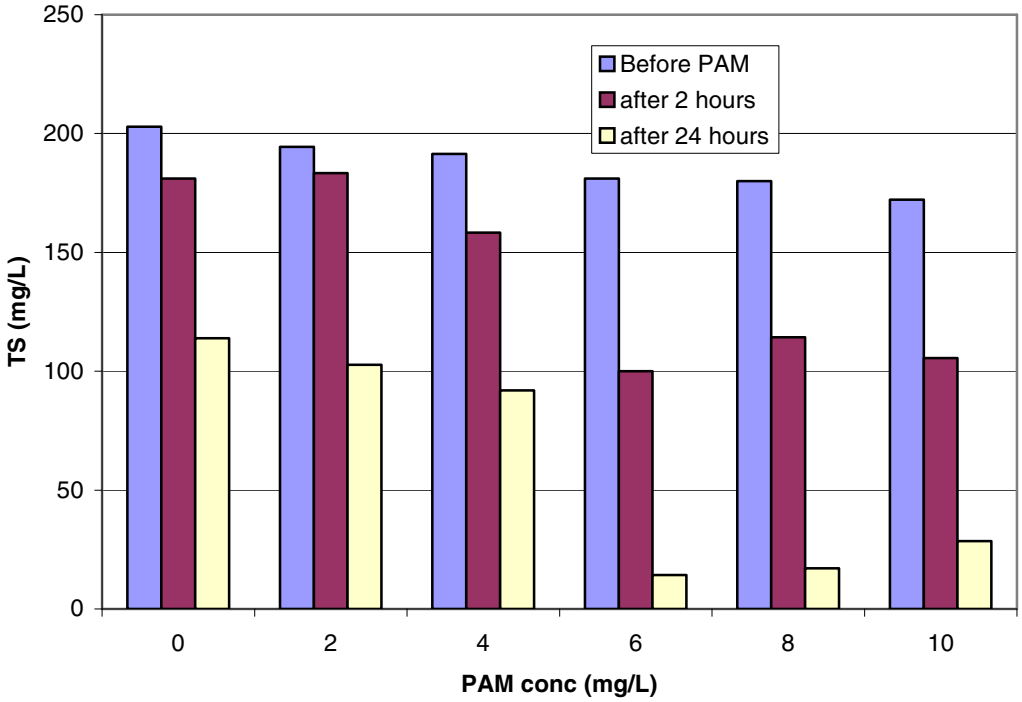

Figure 4.41. TS data with C-448 Lab Test Basin 9 collected December 19, 2005

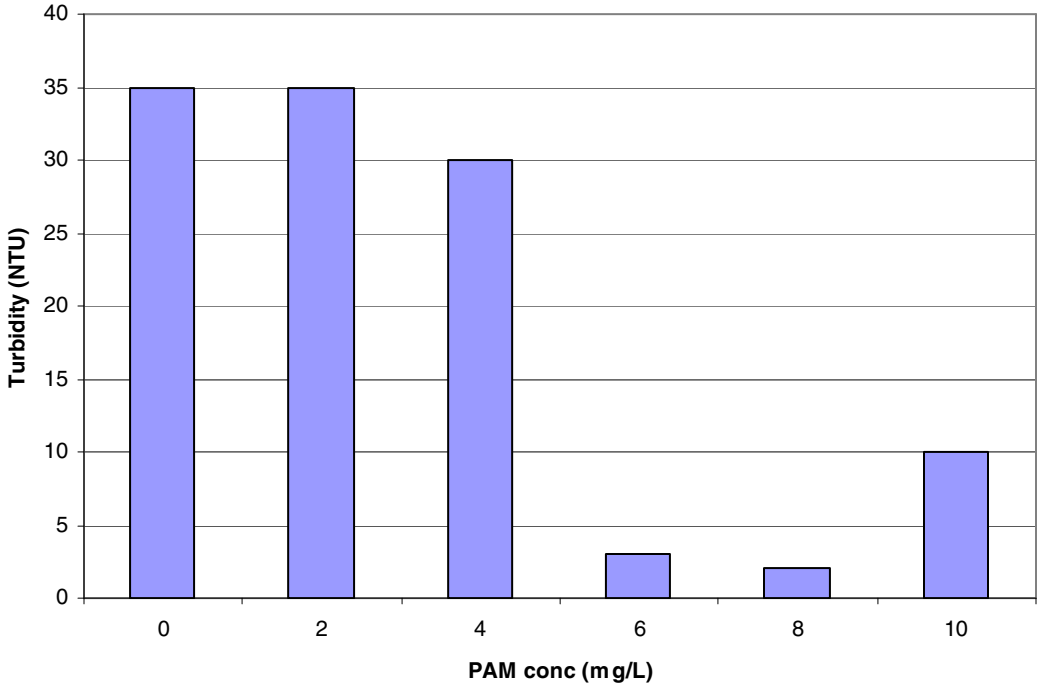

Figure 4.42. Turbidity after 24 hours with C-448 Lab Test Basin 9 collected December 19, 2005

The polymer Superfloc C-498 was tested using stormwater collected from basin 9 on December 19, 2005. The TSS trial showed a 4 mg/L dose producing the best removal, with other doses having negligible removal compared to no coagulant (Figure 4.43). The TS trial shows significant removal for doses of 4, 6, and 8 mg/L (Figure 4.44). The turbidity measurement shows significant reductions at doses 4 mg/L and above (Figure 4.45).

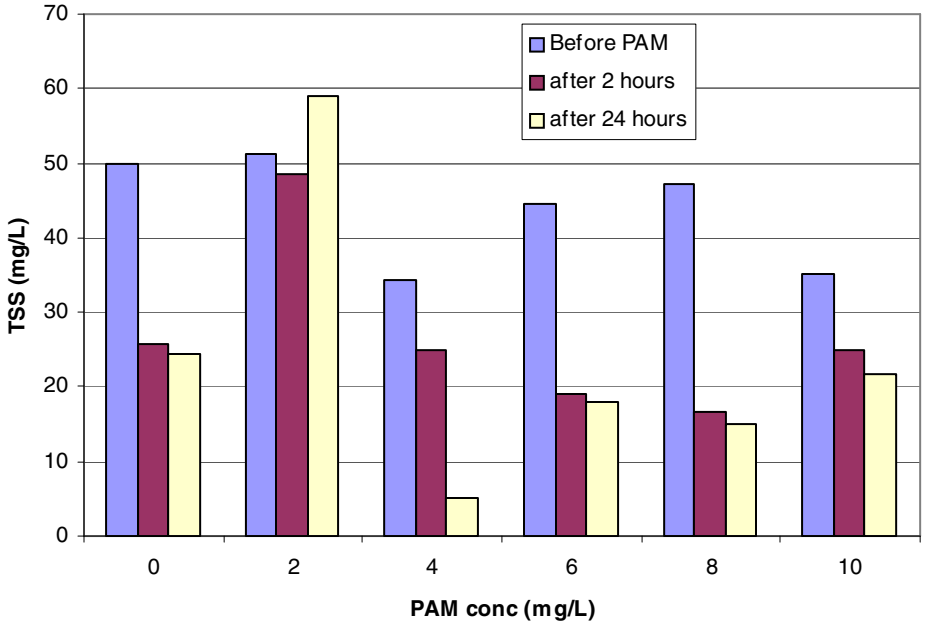

Figure 4.43. TSS data with C-498 Lab Test Basin 9 collected December 19, 2005

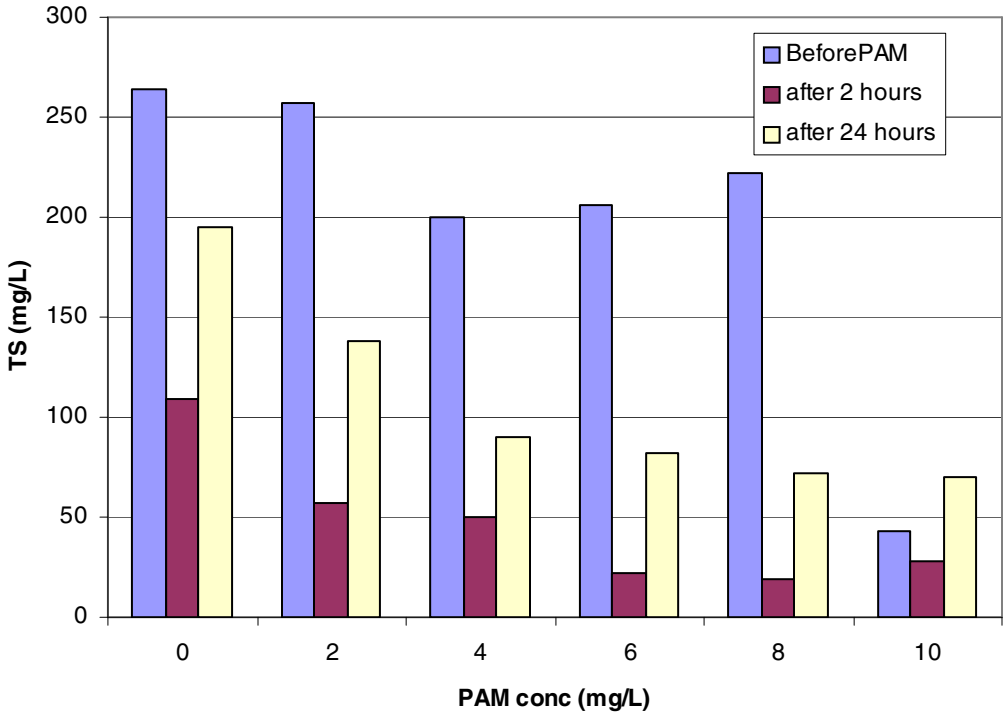

Figure 4.44. TS data with C-498 Lab Test Basin 9 collected December 19, 2005

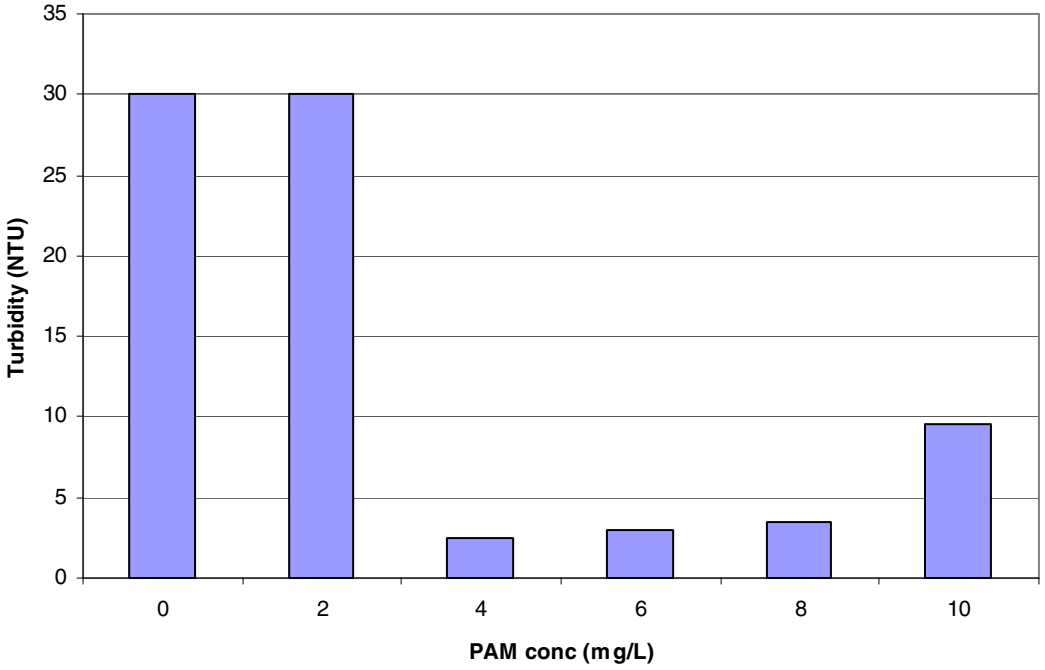

Figure 4.45. Turbidity after 24 hours with C-498 Lab Test Basin 9 collected December 19, 2005

4.3. Comparison of all Coagulants

One method of normalizing the initial polymer and alum data is to take ratios comparing the results using the optimum coagulant concentration to those of the control (no added coagulant). For each comparison, coagulants with low ratios are considered to be the most effective. For turbidity, the ratio of coagulant to no coagulant for final turbidity after 24 hours settling was charted (Figure 4.46). The lowest ratios were seen in C-

448, C-498 and alum. The best anionic polymer ratios were A-100 and A-120, but they were significantly higher than the cations and alum.

Percent removal due to TS was calculated for all coagulants and compared to the percent removal of the control sample of the same trial. These percent removals were than compared no-coagulant to coagulant addition so a small ratio was desired (Figure 4.47). The lowest ratios were noted by A-110 and alum. C-448 and C-498 cationic polymers also had low ratios. No other coagulants had ratios less than 0.5.

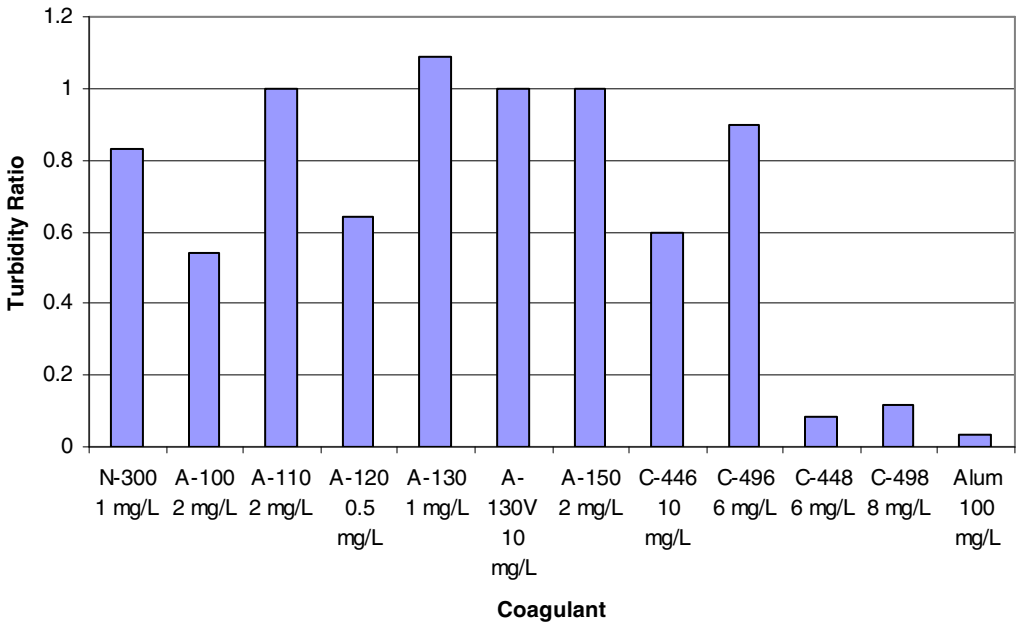

Figure 4.46. Ratio of turbidity after 24 hours of coagulant vis-a-vis no coagulant for all coagulants evaluated in this study

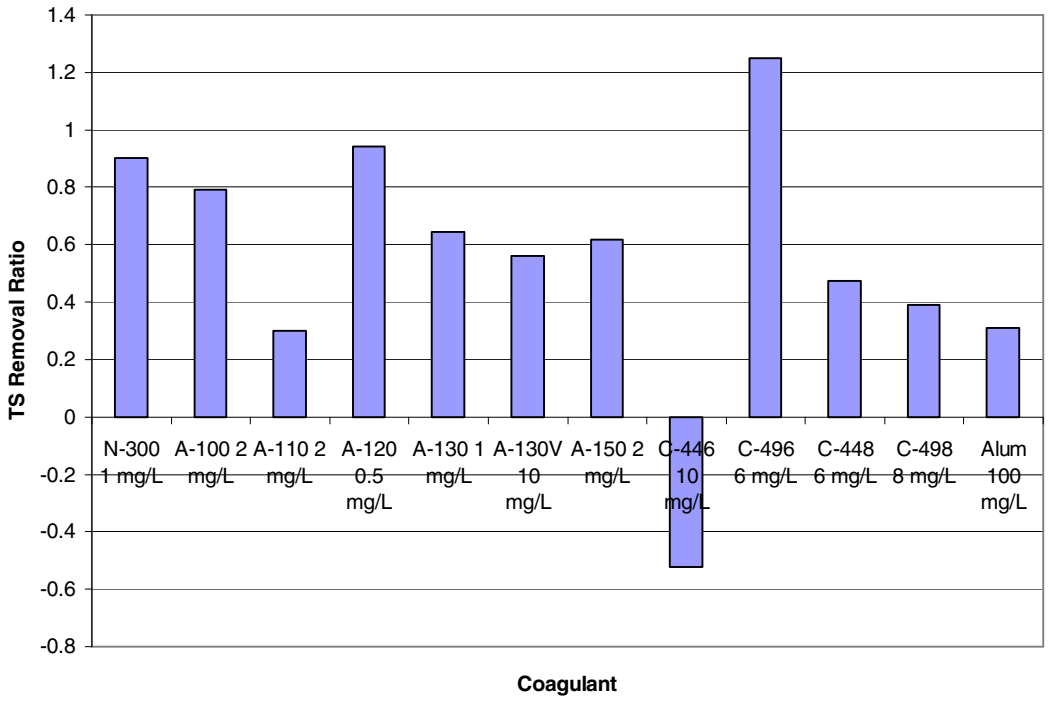

Figure 4.47. Ratio of percent removal TS using no coagulant vis-a-vis coagulant for all coagulants evaluated in this study

These ratios were used to select the coagulants used in the subsequent comparison trial. Since alum had good ratios in both TS percent removal and turbidity it was selected immediately. Both C-448 and C-498 had good ratios, but only one cationic polymer was chosen because the toxicity of cationic polyacrylamides made them undesirable for field usage. C-448 was selected due to its lower turbidity ratio. Anionic polymer A-110 was chosen based on the percent removal ratio and A-100 was chosen because of the low turbidity ratio and because it had demonstrated good performance in previous studies mentioned in the literature review.

Scientifically, cationic polymers and alum are predicted to more efficiently remove sediment than anionic polymers. Natural sediment particles found in stormwater are negatively charged and interactions with positively charged coagulants cause the formation of flocs and increase settling rates. Anionic polymers must take advantage of the innate presence of dissolved cations in the stormwater and clay content in the soil (Lu et al. 2002, Vacher et al. 2003). The anionic polymers with the smallest negative charges, A-100 and A-110, were slightly more efficient than other anionic polyacrylamides. This could possibly be attributed to Van de Waals forces working in combination with the cation-bridging mechanism proposed in the literature (Lu et al. 2002).

4.4. Coagulant Comparison Laboratory Tests

Four lab trials were conducted comparing four different coagulants selected above (Figures 4.48-59). Four trials were conducted to demonstrate the reproducibility of the coagulant effectiveness testing. A-100, A-110, C-448, and alum comparison trials were performed following the Coagulant Selection Protocol (Section 3.6) designed for determining the optimum coagulant for a specific basin location. The sample stormwater and sample soil both were collected from basin 7 on April 14, 2006. In all four trials, the

coagulants outperformed the control sample in TSS and TS removal and turbidity reduction. However, due to the scale of the TSS and TS charts, the difference between no coagulant and coagulant is most noticeable in turbidity graphs (Figures 4.50, 4.53, 4.56, and 4.59). In trial 2, a concentration of 75 mg/L of alum was added to samples instead of 100 mg/L because the samples could not accommodate the full dose. In the original laboratory trials, alum was effective at all doses over 60 mg/L and the difference between 80 mg/L and 100 mg/L was slight. In the Coagulant Comparison trials, the 75 mg/L dose of trial 2 slightly outperformed the 100 mg/L doses of alum in the three other trials (4.51-53).

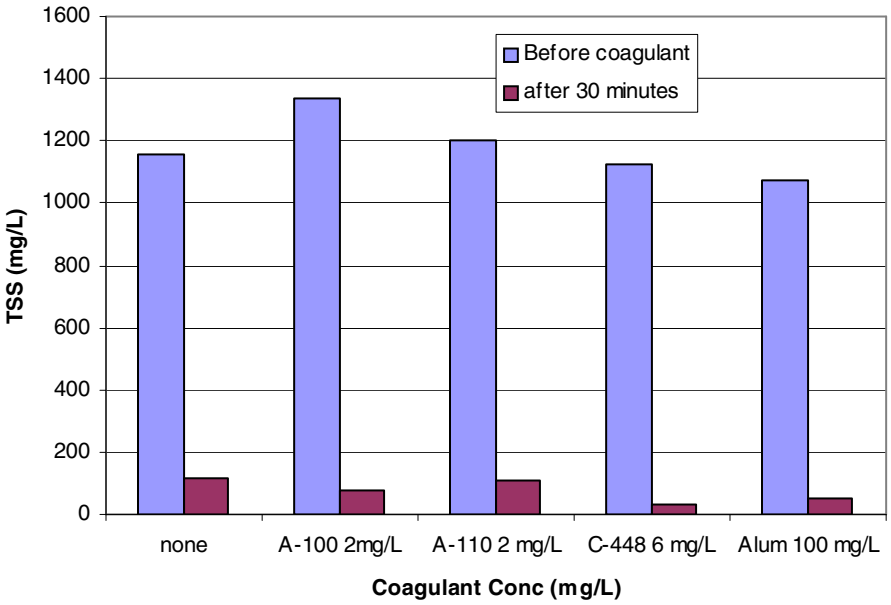

Figure 4.48. TSS data for Coagulant Comparison Lab Trial 1 Basin 7 collected April 14, 2006

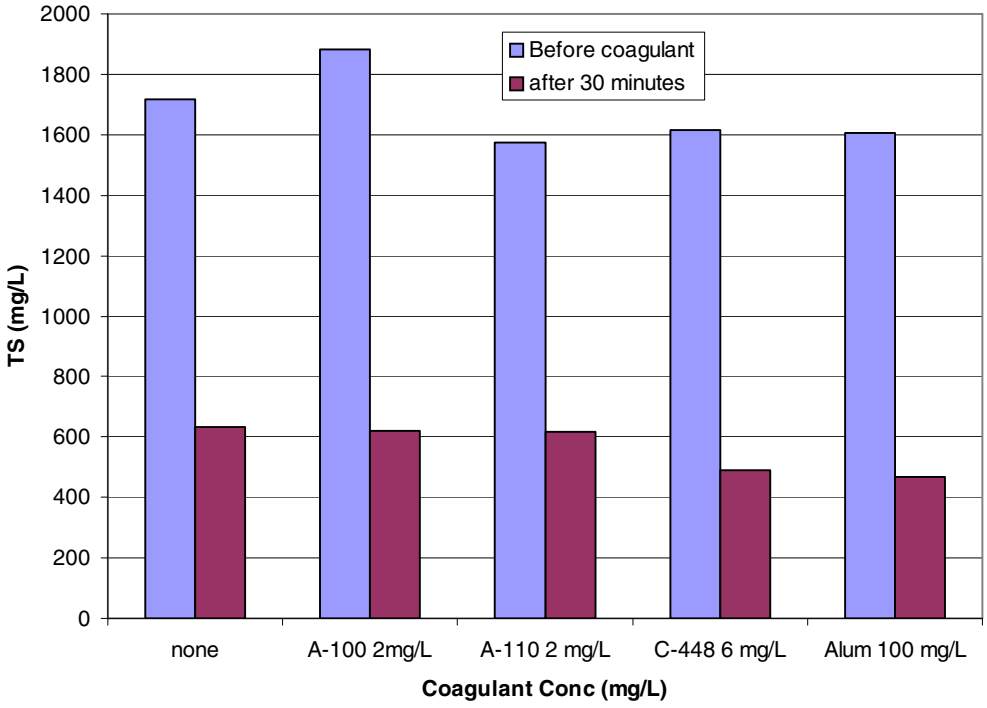

Figure 4.49. TS data for Coagulant Comparison Lab Trial 1 Basin 7 collected April 14, 2006

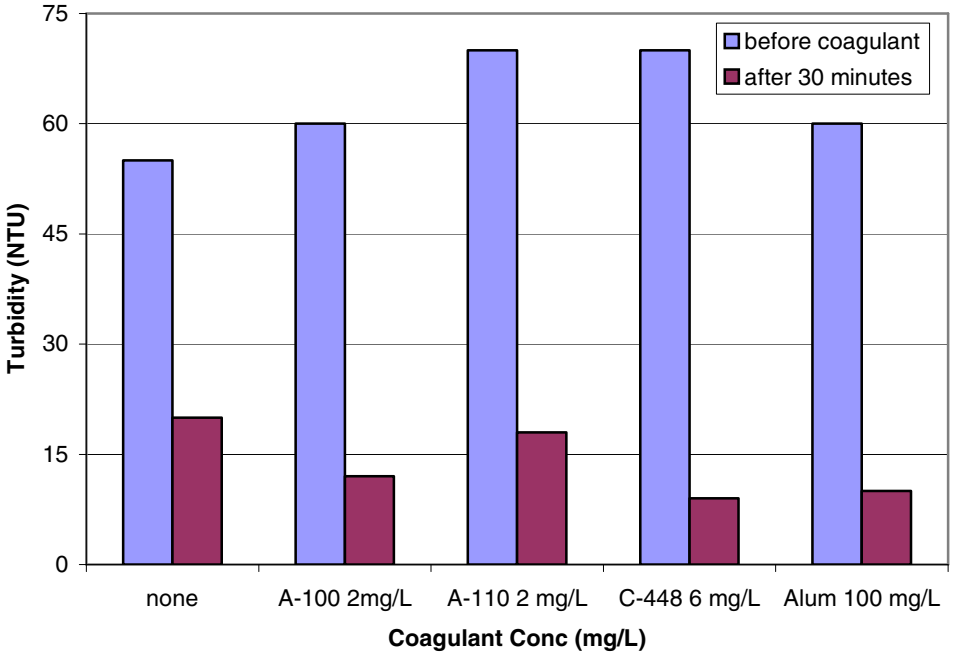

Figure 4.50. Turbidity data for Coagulant Comparison Lab Trial 1 Basin 7 collected April 14, 2006

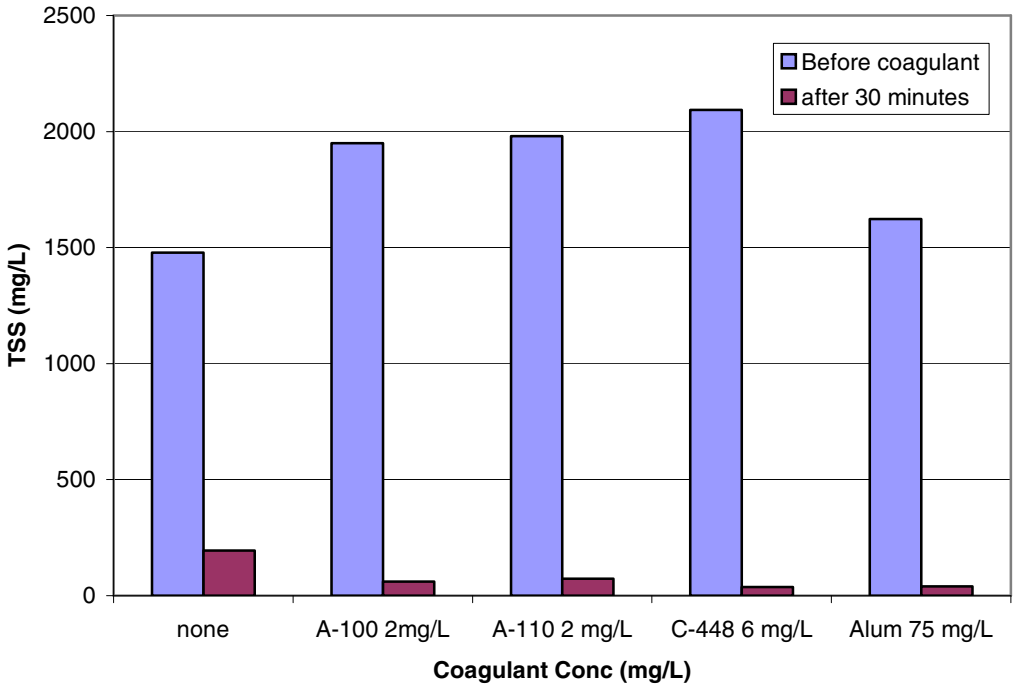

Figure 4.51. TSS data for Coagulant Comparison Lab Trial 2 Basin 7 collected April 14, 2006

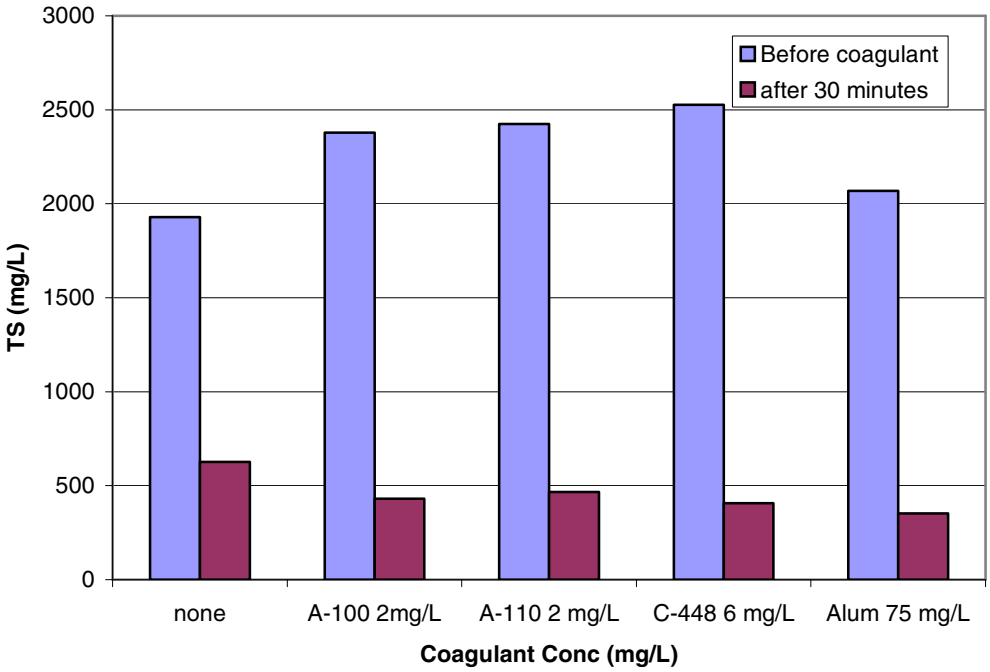

Figure 4.52. TS data for Coagulant Comparison Lab Trial 2 Basin 7 collected April 14, 2006

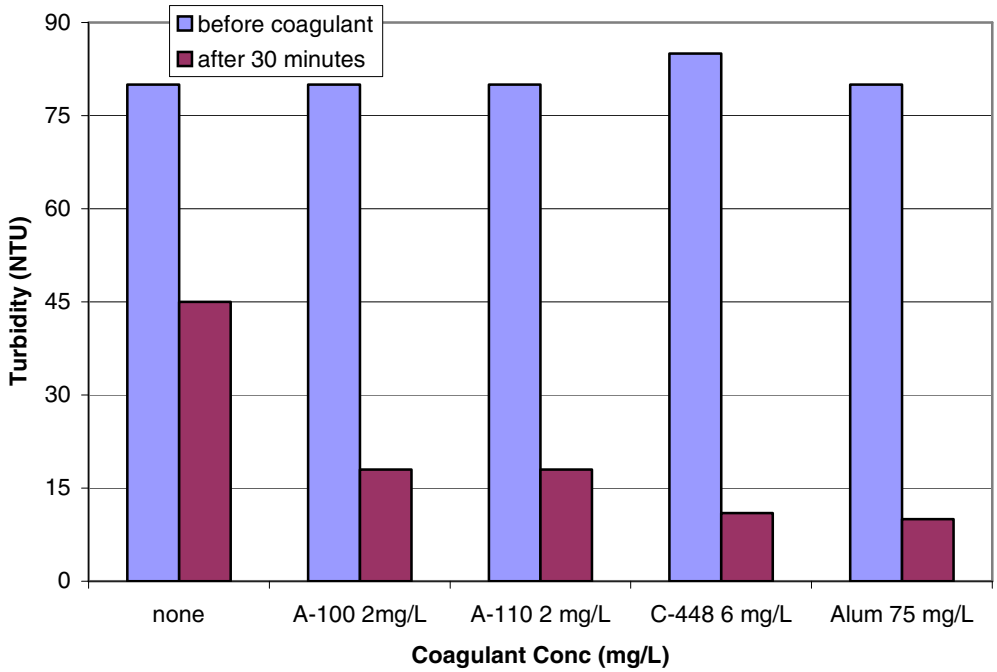

Figure 4.53. Turbidity data for Coagulant Comparison Lab Trial 2 Basin 7 collected April 14, 2006

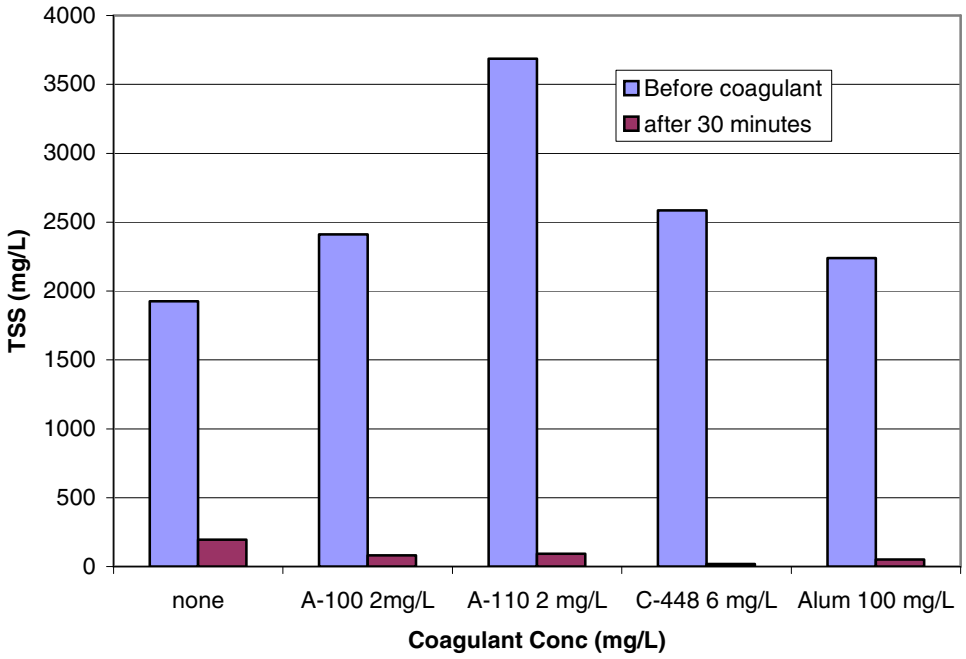

Figure 4.54. TSS data for Coagulant Comparison Lab Trial 3 Basin 7 collected April 14, 2006

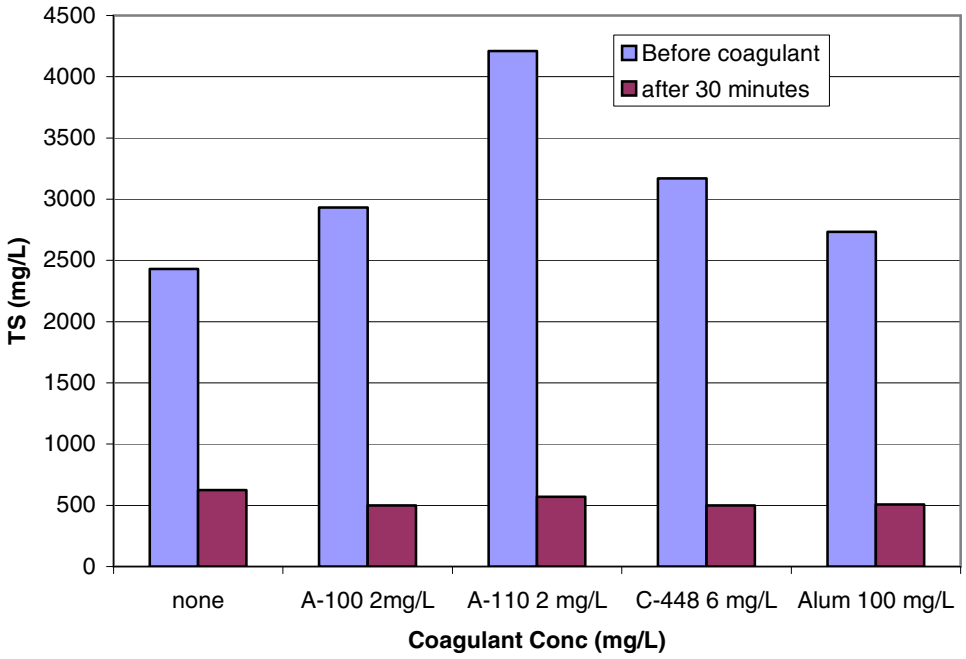

Figure 4.55. TS data for Coagulant Comparison Lab Trial 3 Basin 7 collected April 14, 2006

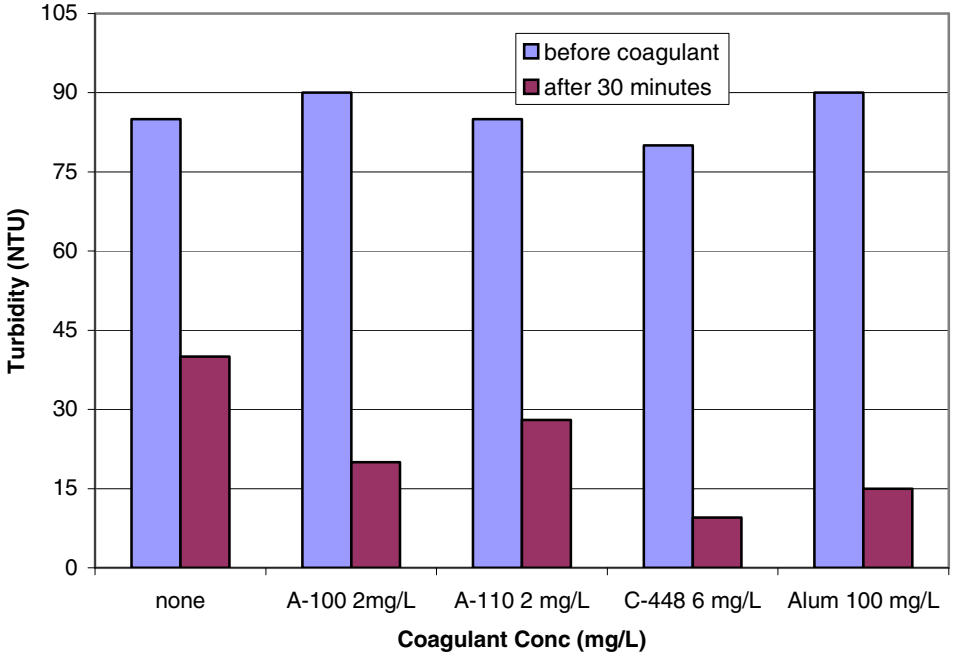

Figure 4.56. Turbidity data for Coagulant Comparison Lab Trial 3 Basin 7 collected April 14, 2006

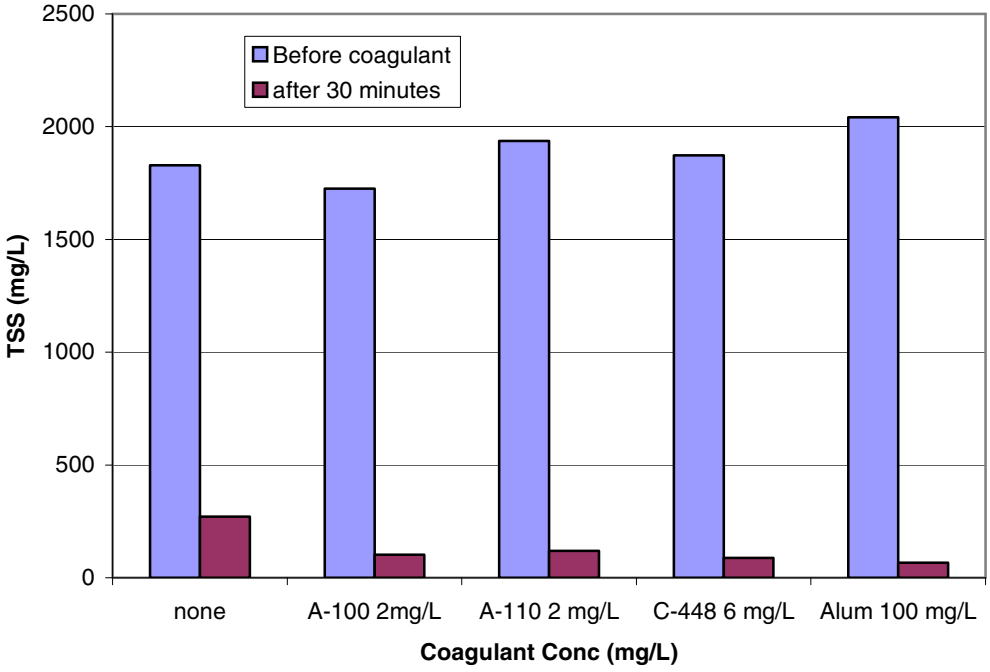

Figure 4.57. TSS data for Coagulant Comparison Lab Trial 4 Basin 7 collected April 14, 2006

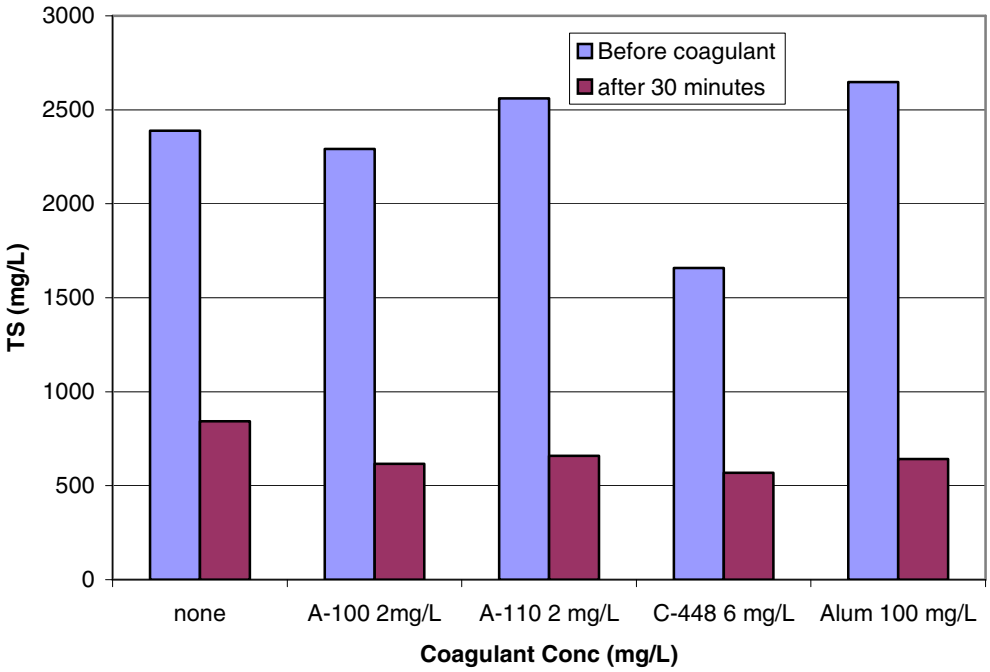

Figure 4.58. TS data for Coagulant Comparison Lab Trial 4 Basin 7 collected April 14, 2006

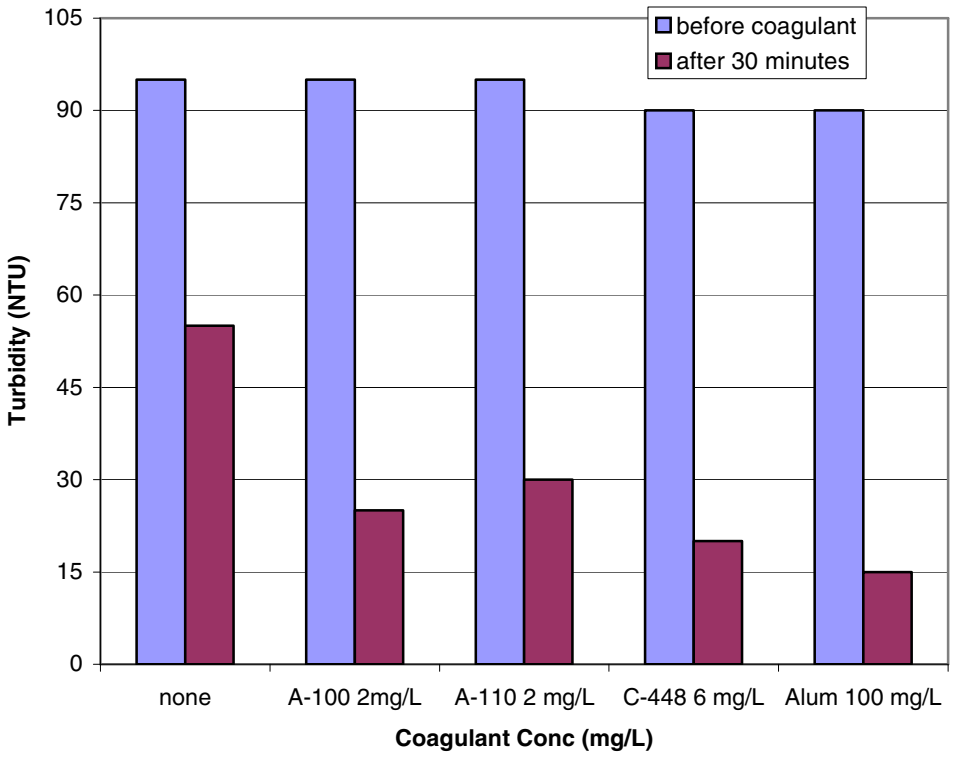

Figure 4.59. Turbidity data for Coagulant Comparison Lab Trial 4 Basin 7 collected April 14, 2006

Table 4.1. Results of Coagulant Comparison Lab Trials Basin 7 April 14, 2006 after 30 minute settling time

Coagulant	Dose (mg/L)	Average % removal TSS	P-value	Average % removal TS	P-value	Average % reduction turbidity	P-value
No coagulant	None	88 +/- 2.4		68 +/- 4.8		51 +/- 10.0	
A-100	2	96 +/- 1.7	0.002	76 +/- 7.6	0.100	78 +/- 2.5	0.002
A-110	2	95 +/- 3.0	0.013	76 +/- 10.8	0.208	72 +/- 5.2	0.010
C-448	6	97 +/- 1.7	0.001	76 +/- 9.4	0.158	85 +/- 4.7	0.001
Alum	100	97 +/- 1.4	0.001	78 +/- 5.4	0.029	84 +/- 2.5	0.001

Table 4.1 gives a summary of the Coagulant Comparison Trial results. The most significant reductions were in turbidity and with doses of C-448 and alum. The polymer A-110 was the least effective of the coagulants, but only marginally in TSS and TS. Over 4 trials with each coagulant and the control, the results were consistent, with low standard deviations. Therefore, using the Coagulant Selection Protocol, presented in Section 3.6, similar results can be reproduced at other potential field sites.

A student's t-test was performed comparing each coagulant directly to the control samples. The t-test compares the means and standard deviations of the samples to determine if they are same or different. A p-value is calculated to assess the probability that the samples have the same mean. Table 4.1 lists the calculated p-values for each coagulant as compared to the no coagulant control sample. For the TSS and turbidity tests, all coagulants have greater than 95% probability of different means than the control. For the TS test, only Alum has a greater than 95% probability of being different. The student's t-test confirms the results that coagulants increased efficiency in TSS removal and turbidity reduction over the no coagulant control.

4.5. Laboratory pH study

A pH study was conducted following the same protocol as the coagulant comparison to determine the effect of pH on TSS removal and turbidity reduction. An additional goal of this test was to determine if coagulant had an effect on pH, particularly alum. The addition of coagulant did not change the pH of the sample during sampling. A New Zealand study reported that 5.5 mg/L of alum reduced pH in stormwater by 0.5 units. A TS test was not performed for this study because the normalization issue observed during the first laboratory trials was not noted during the Coagulant Comparison Trials. Coagulants A-100, C-448, and alum were tested, along with a no coagulant control, at pH values of 5.66, 6.5, 7.45, and 8. The ambient pH was 7.45 and 0.1 M HCl and 0.1 M NaOH were used to adjust the pH of the samples. Very little effect was noticed on TSS measurements, however for the three coagulants, a pH of 5.66 had slightly less removal than other levels (Figures 4.60-63). For the control, pH of 7.45 had less removal. Also, minimal effects were noted on turbidity measurements, but pH 5.66 consistently had slightly less removal than other values for all samples (Figures 4.64-67).

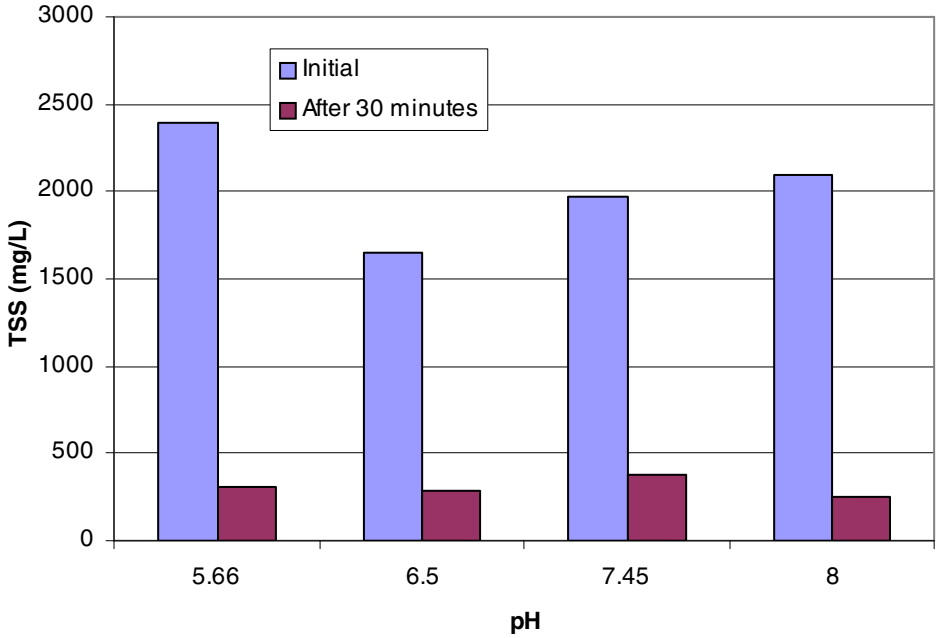

Figure 4.60. TSS data for no coagulant Lab Trial pH study Basin 7 collected May 4, 2006

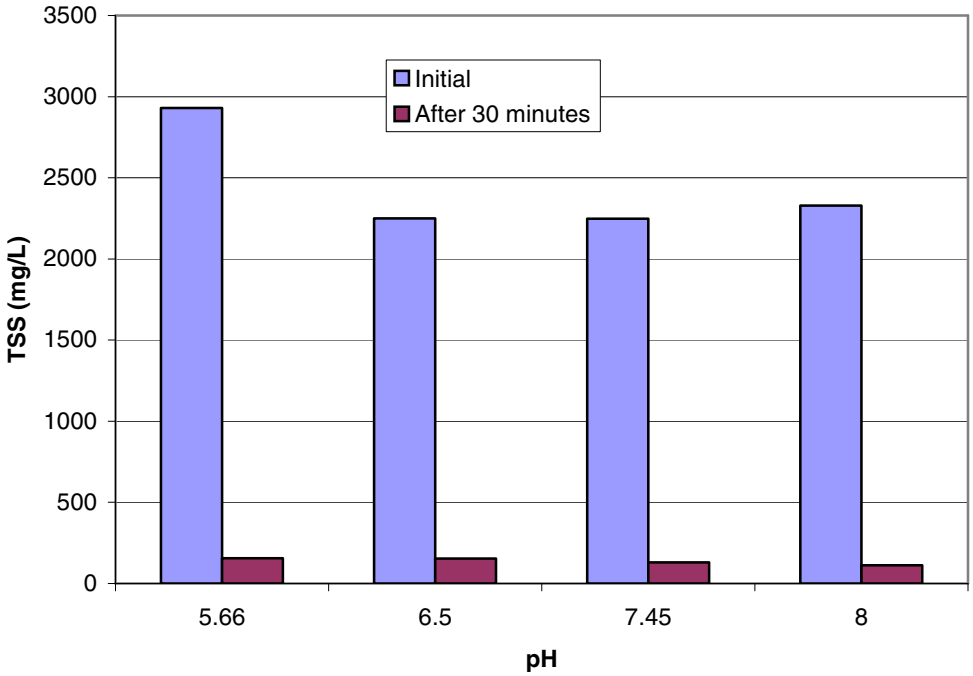

Figure 4.61. TSS data for A-100 at 2 mg/L Lab Trial pH study Basin 7 collected May 4, 2006

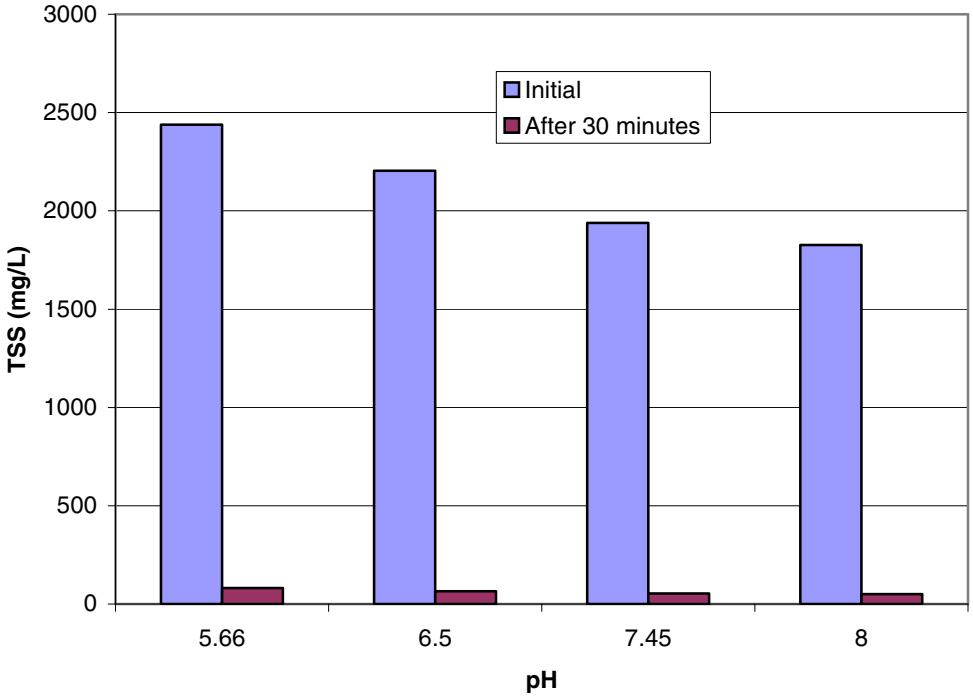

Figure 4.62. TSS data for C-448 at 6 mg/L Lab Trial pH study Basin 7 collected May 4, 2006

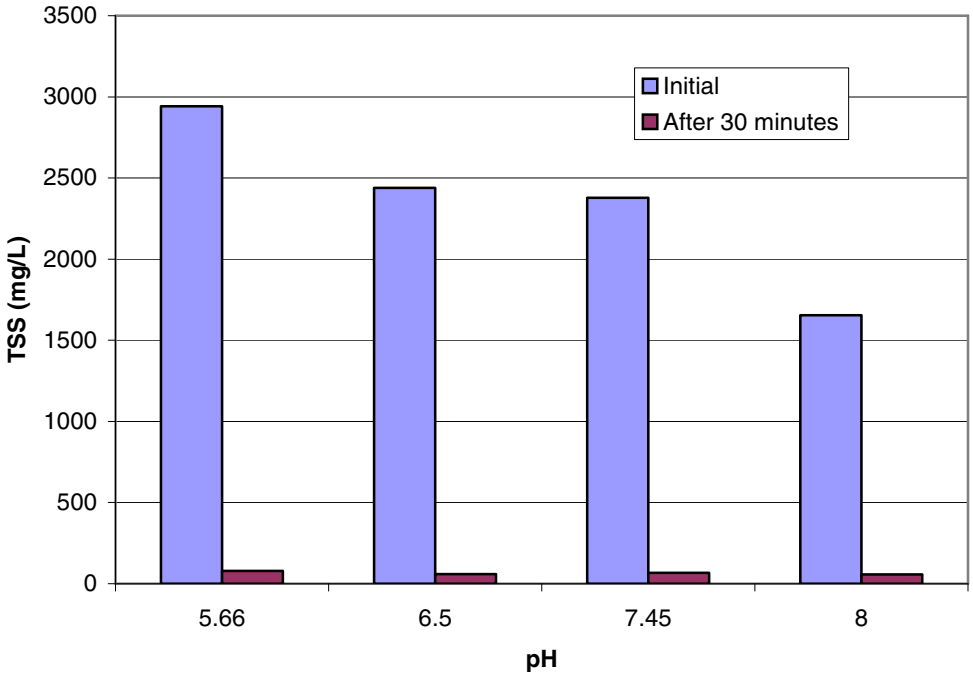

Figure 4.63. TSS data for alum at 100 mg/L Lab Trial pH study Basin 7 collected May 4, 2006

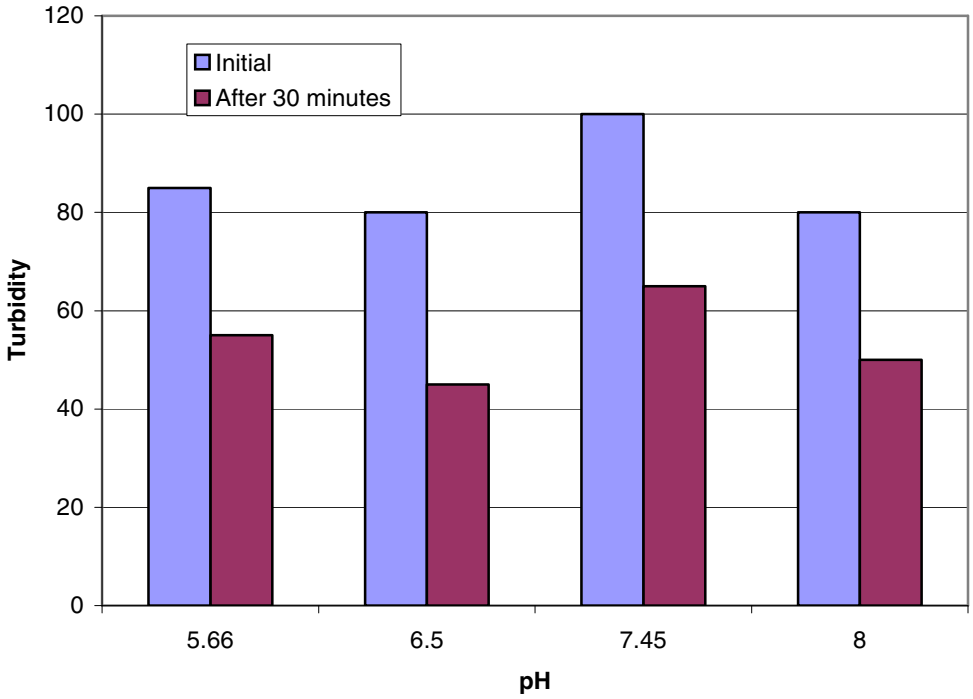

Figure 4.64. Turbidity data for no coagulant Lab Trial pH study Basin 7 collected May 4, 2006

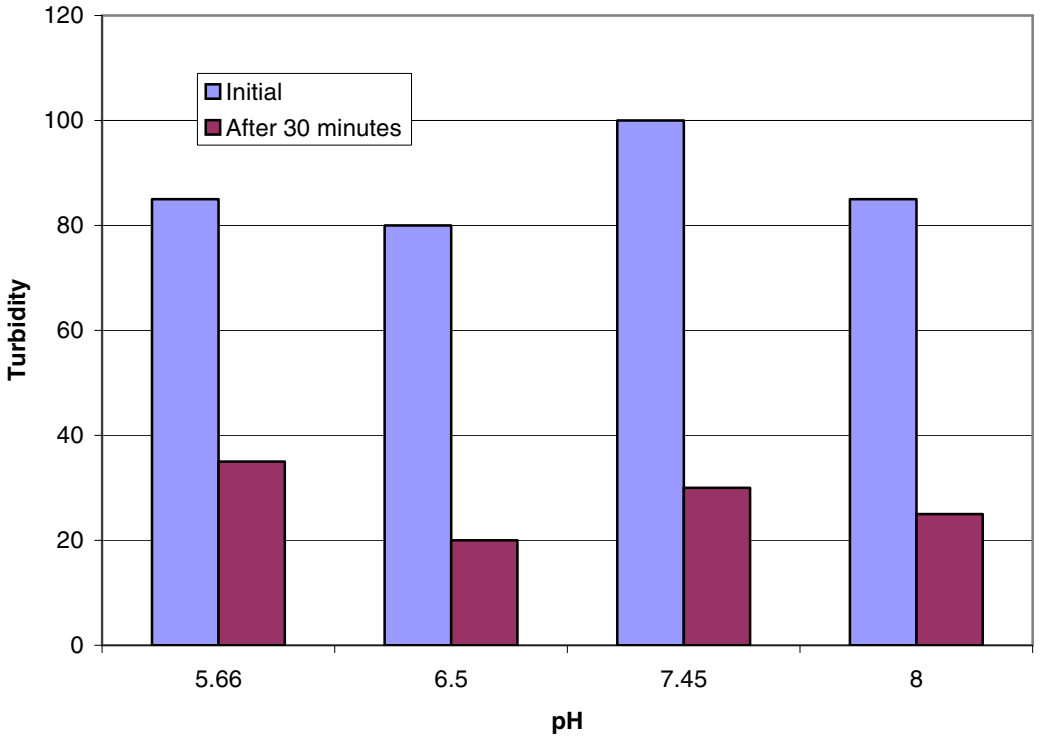

Figure 4.65. Turbidity data for A-100 at 2 mg/L Lab Trial pH study Basin 7 collected May 4, 2006

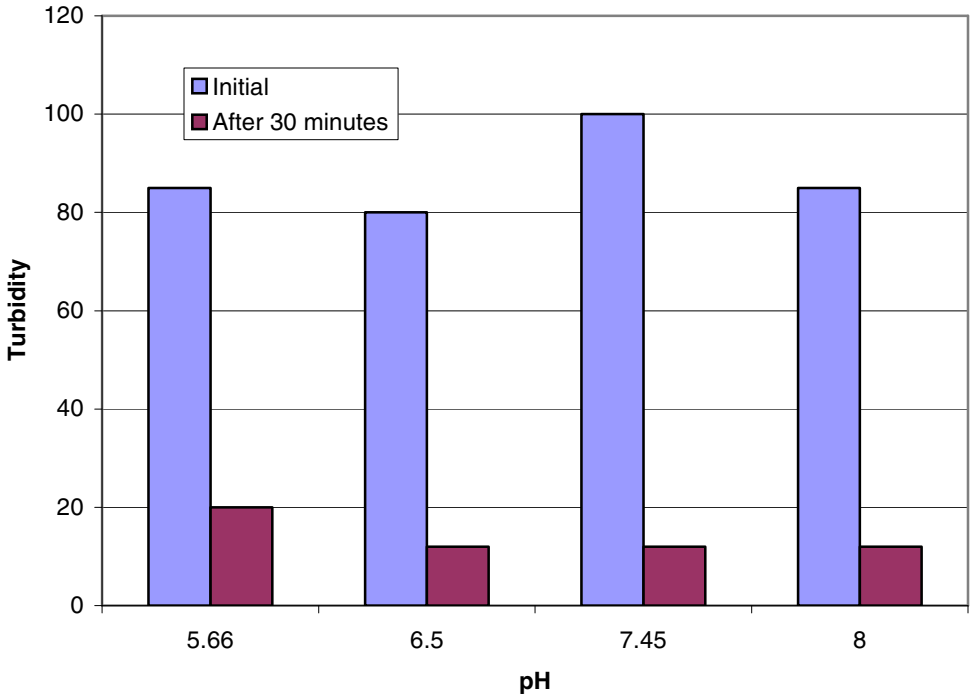

Figure 4.66. Turbidity data for C-448 at 6 mg/L Lab Trial pH study Basin 7 collected May 4, 2006

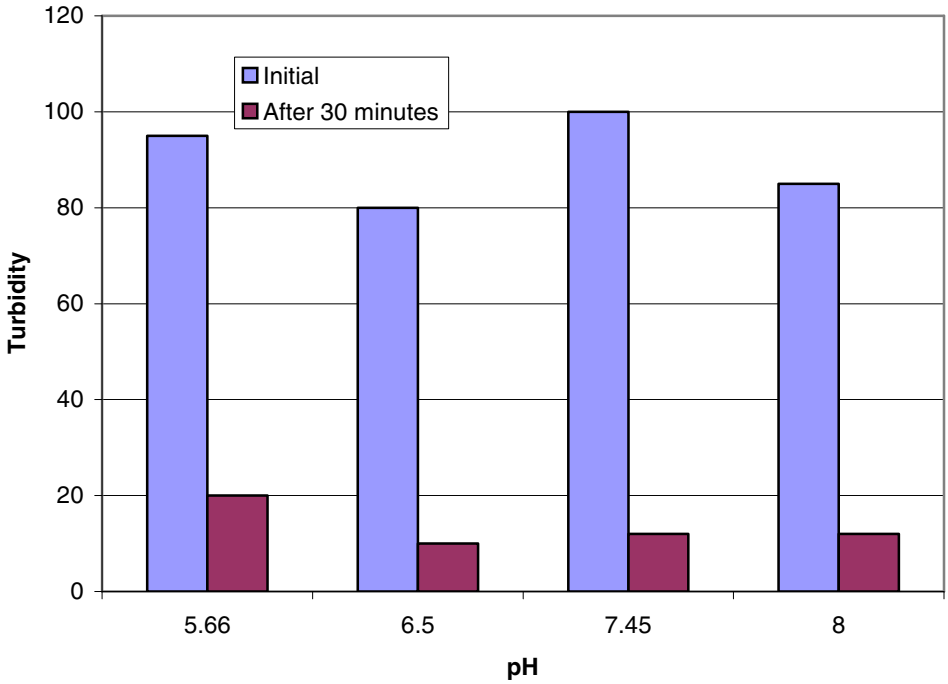

Figure 4.67. Turbidity data for alum at 100 mg/L Lab Trial pH study Basin 7 collected May 4, 2006

4.6. Summary

In this study, a preliminary field test was conducted, multiple laboratory trials were conducted with a variety of coagulants and a protocol was developed to select the optimum coagulant for the MD 43 field site. A pH study was conducted with the most effective coagulants.

The preliminary field test was visibly ineffective and led to the laboratory tests to determine if coagulants would be effective at the MD 43 site. After the laboratory trials were conducted with various coagulants at

various doses, A-100, A-110, C-448, and alum were chosen as the most effective and in need of controlled study. All four coagulants were more efficient at removing sediment than the not using coagulant. The pH study did not demonstrate performance differences among the coagulants over the pH range of 5.66 to 8. The results demonstrated the potential for coagulants to be used in construction site stormwater and a protocol was developed to reproduce the trials for any construction site sedimentation basin.

Chapter 5. Field Testing Design

5.1. Testing Basin Characteristics

Field testing of laboratory results is the next logical step for this project. The main difference between a construction site sedimentation basin and a water treatment sedimentation basin is that a rapid mix process precedes the water basin. This rapid mix is desirable for encouraging interactions between the coagulant and the suspended solids. For coagulant use to be effective at a construction site, a rapid mix process must precede the sedimentation basin. One option is to install an additional basin that contains a small motorized mixer. This is feasible, but not practical for space, maintenance, and design considerations. Another option is to utilize a riprap inlet as a rapid mix process. Riprap is often present on many existing sedimentation basins and does not require any additional maintenance for the basin.

5.1.1. Riprap Channel Design

For a coagulant-assisted stormwater basin to be effective in the field the coagulant must be well mixed with the water. The mixing increases the particle-coagulant interactions, which increases floc growth and the

subsequent removal of TSS and reduction of turbidity. The basins themselves lack the inherent mixing capacity for the coagulant to be effective, so an alternative procedure must be developed. Due to the average size of a basin being hundreds of cubic meters, a large mixing device in the pond is likely to be cost prohibitive. Mixing the coagulant with the runoff as it enters the basin is a more feasible alternative.

Manning's equation was used for the calculation of channel design:

$$Q = \frac{C_m}{n} A(R_h)^{2/3} S^{1/2} \qquad (5.1)$$

where Q is the volumetric flow rate of the runoff. This was set at 0.142 m^3/s for design purposes as a reasonable expected load for a basin (Maryland Department of the Environment 1994). C_m is a conversion factor of 1.49. Manning's n was determined to be approximately 0.05 for an open riprap channel (Akan 2006). The slope, S, is defined as the elevation change divided by the length of the channel. The area of the channel, A, is defined as the flow area at normal depth, y. The hydraulic radius R_h is defined as the area of the flow divided by the wetted perimeter, and thus is also a function of the normal depth. The channel was designed as a trapezoid with side slopes of 0.5 (Figure 5.1).

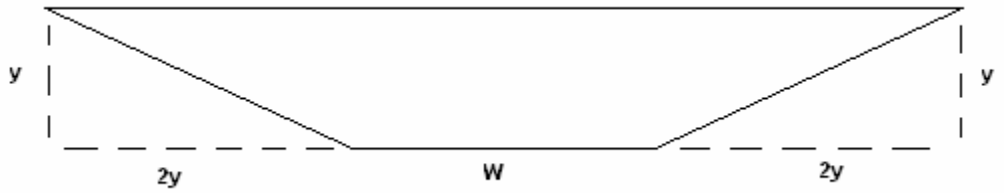

Figure 5.1. Shape of Riprap Inlet Channel for Sedimentation Basin; W = width, y = normal depth

The velocity gradient G equation (Reynolds 1982) was used to calculate head loss per time in the channel. The velocity gradient is a common formula used in water and wastewater treatment processes to define mixing. G values between 700 and 1000 s^{-1} are considered rapidly mixed (Reynolds 1982).

$$G = \left[\frac{W}{\mu}\right]^{\frac{1}{2}} = \left[\frac{P}{\mu V}\right]^{\frac{1}{2}} \tag{5.2}$$

Where G is the velocity gradient in s^{-1}, W is the work, or power P per volume V with units N-m/s-m^2, and μ is the viscosity of water. Converting the work to head loss per time yields:

$$G = \left[\frac{\gamma Q h}{\mu V}\right]^{\frac{1}{2}} = \left[\frac{h\gamma}{t\mu}\right]^{\frac{1}{2}} \tag{5.3}$$

where the head loss per time is h/t.

Figure 5.2 was developed by using the velocity gradient and Manning's equations to develop a relationship between width and slope of a

channel for a fixed velocity gradient and runoff flow rate (0.142 m^3/s, 5 ft^3/s). This flow rate was chosen as a reasonable flow rate for Maryland stormwater runoff. An increased flow rate will increase the area of the flow and a wider channel may be needed. The selected velocity gradient was used to determine the head loss per time. The head loss per time divided by the slope of the channel is equal to the runoff velocity through the channel. The area of the flow through the channel is then defined as the chosen flow rate divided by the velocity. With the area known, only normal depth, as a function of hydraulic radius, is the only unknown in Manning's equation. The given parameters were used in combination with an MS Excel solver function to approximate normal depth under these conditions. The normal depth was then used to calculate the width of channel required to meet the given slope and velocity gradient. The results were then plotted for corresponding widths and slopes at different G mixing values, but constant runoff flow rate. The minimum width allowed by Maryland law for a riprap inflow channel is 0.9 m (MDE 1994), which limits the mixing at low slopes.

The width versus slope channel relationship is important to obtaining the desired degree of rapid mixing provided by the riprap inlet. During the basin design process, it may only be feasible to alter either the channel width or slope. In those instances, the corresponding slope or width can be

determined using Figure 5.2. The relationship between width and slope is intuitive given that the purpose of riprap is to lessen the velocity of the incoming runoff. As slope increases, the water flow rate increases and thus the width must be greater to maintain the same velocity. It is also intuitive that the higher velocity gradient occurs in wide channels and steep slopes. The wide channel decreases the normal depth and thus decreases the volume of water passing over the friction of the riprap. With a steeper slope, there is a faster velocity through the riprap, which creates more turbulence and thus more rapid mixing.

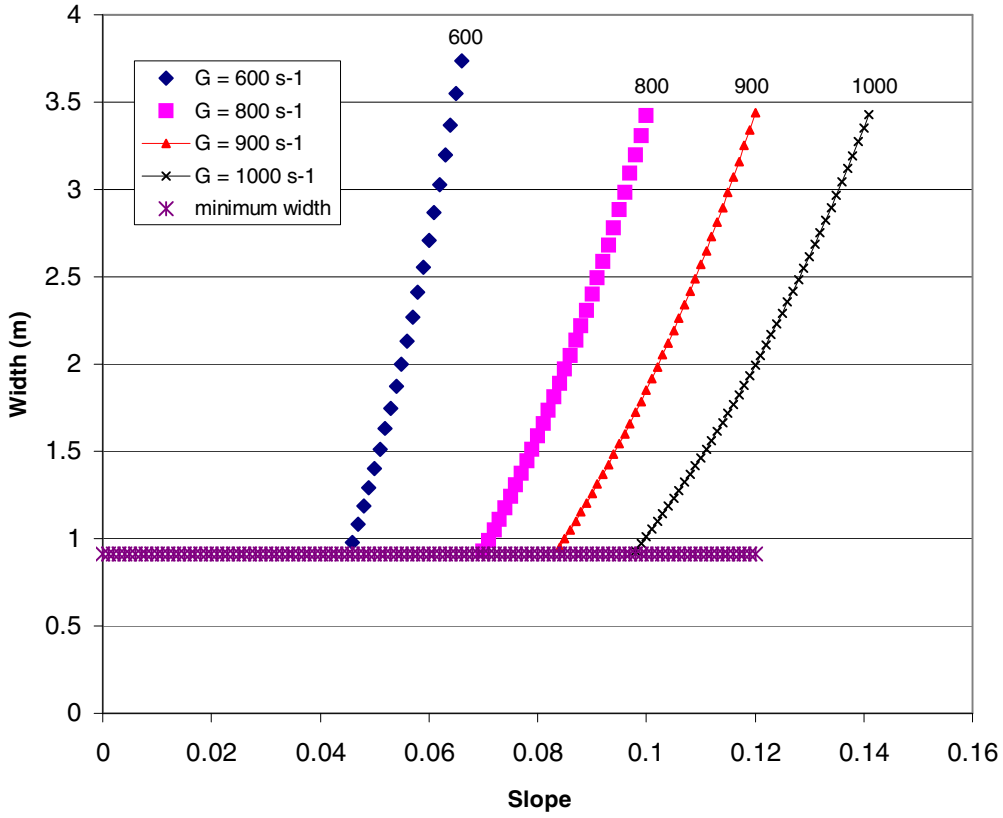

Figure 5.2. Width vs. Slope ratios for different G mixing values of riprap inflows, Q = 0.142 m^3/s (5 ft^3/s). Select G for mixing. At given riprap channel slope, select width to provide adequate mixing.

5.1.2. Sedimentation Basin

For proper field testing, an appropriate sedimentation basin should be chosen, or more ideally, be designed for testing purposes. Several characteristics should be considered when choosing a basin for field testing.

To simplify the coagulant dosing and sample collections, the basin should have only one inlet and one outlet. Having one inlet insures that the

majority of stormwater enters the basin in a controlled fashion. Some stormwater will inevitably enter from the sides of the pond. If there are two or more inlets, the inlet supporting the largest bare soil drainage area should be chosen for testing or additional dosing systems should be installed. Effectiveness of the coagulant may also be harder to discern with more than one inlet. A single inlet and single outlet for stormwater simplifies sample collection to only two locations.

The mixing characteristics of the basin should also be considered. A long narrow basin with parallel sides is desirably for having mixing characteristics that approach a plug-flow reactor. This insures a small range of residence times for stormwater entering the basin and nearly equivalent sediment concentrations as water moves throughout the basin. Irregularly shaped basins can lead to a wide variety of residence times and have a greater potential for stagnant "pooling" areas where no mixing occurs.

The primary inlet for stormwater runoff is also important because it will determine the setup of the dosing system. For proper coagulation and flocculation to occur, the coagulant must interact with the sediment particles through rapid mixing. Riprap can provide ample mixing at proper widths and slopes (Figure 5.2). With riprap providing the rapid mixing, the coagulant can be input at the top of the inlet. If riprap is not used for inflow

conveyance, another method of rapid mixing must be installed for proper dosing of the coagulant. If the inflow is designed for specific use with coagulants, a weir should be installed. With the weir, the flow rate of the incoming stormwater can be known and eliminate the need for estimates.

5.2. *Equipment Needed*

With the rapid mix process included in the sedimentation basin, the next step is installation of an automated coagulant dosing system. This system will input coagulant into the flowing runoff at the start of the riprap inlet. The automated system will allow precise control over coagulant dosage. A list of necessary equipment is given below; Figure 5.3 illustrates the setup for automated coagulant dosing.

- Flow sensor/Rain gauge – the flow sensor should be used if the weir is installed. It will measure the height of stormwater entering the basin at the inlet and convert that value to flow rate. A rain gauge should be used if a weir is not installed to continuously measure the intensity of the rain. The rainfall intensity can then be used to estimate the flow rate with knowledge of the drainage area. Both the flow sensor and the rain gauge should take measurements in increments of 3-5

minutes or less so as not to overdose the inflow with coagulant.

- Controller – should be compatible with output signals of the flow sensor/rain gauge. The controller will interpret signals from the flow sensor/rain gauge to a readable value. An output signal is a required specification of the controller. This may be unnecessary if the flow sensor/rain gauge displays readable values and has an output signal compatible with the dispenser.
- Digital Dispenser – should be able to receive signals from the controller and interpret the proper flow rate of coagulant. The dispenser will control the actions of the pump.
- Coagulant Pump – should have a pumping range of approximately 1-20 L/s and be compatible with the digital dispenser.
- Plastic Tubing – should be compatible with pump and coagulant, with enough length to stretch from the coagulant storage area to the inlet weir.
- Coagulant Stock Solution – coagulant should be chosen based on laboratory tests using the Coagulant Selection Protocol

developed in Section 3.6. Stock solution should be prepared at a concentration that minimizes onsite storage and can be mixed easily. High concentrations of polymers can create a very viscous liquid. Onsite storage should be the amount required to dose a 10 year storm event.

- Power Source – the power source for each individual component will vary, but it is likely that an external power source will be required. A small generator equipped to handle 8-10 hours of nonstop use should suffice. A car battery can be used as a 12V DC power source if needed.
- Equipment Housing – some of the required electronics may require shelter from the elements. A small wooden structure with a metal roof can be used as long as it provides easy access to the equipment.
- Technican – a single person should be able to handle the setup, sample collection, and maintenance to the system. The setup requires system calibration, generator fuel/recharged batteries, and stock solution mixing. At set intervals, samples must be collected from the inlets and outlets as well as various points in the basin. The container from which the pump is

pulling coagulant may need to be refilled during operation. General checkups should be made during the storm event to ensure normal operation.

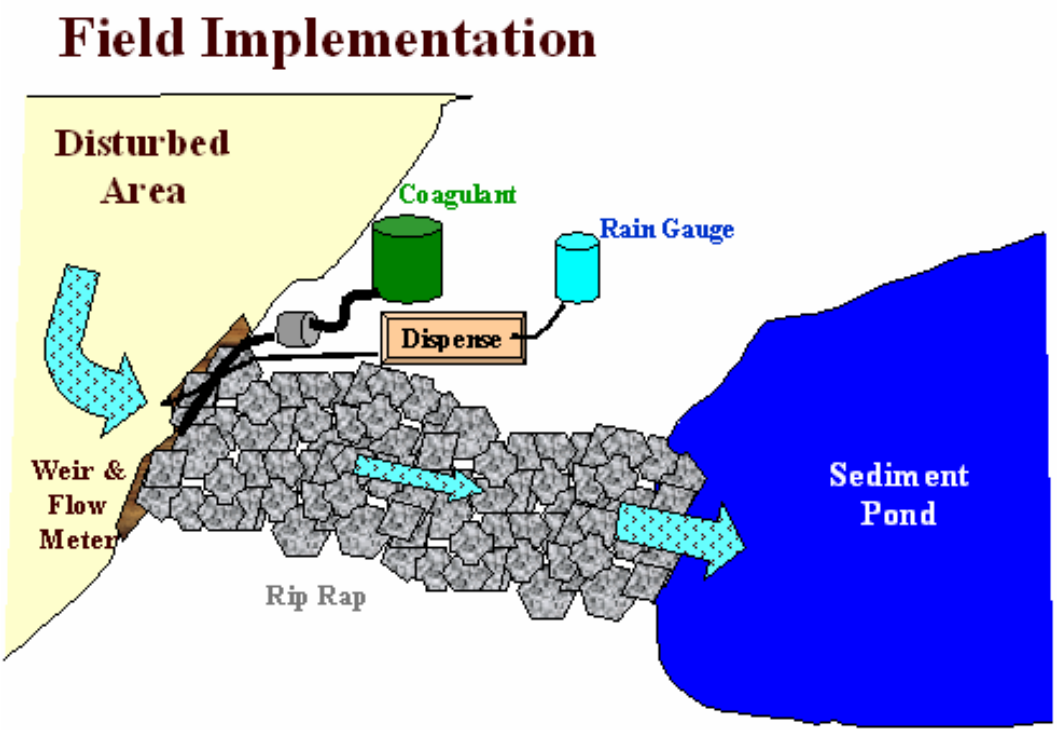

Figure 5.3. Field Implementation Schematic for Coagulant-assisted Sedimentation Basins

5.3. Installation

For installation, the flow sensor will be mounted to the weir. A cable must run from the sensor to the controller. The controller converts the raw data of the sensor into a current signal that can be read by the digital dispenser. The digital dispenser must be calibrated to interpret the flow

signal and apply the proper amount of coagulant using the pump. A cable connects the dispenser to the pump. The controller and the dispenser must be located inside the protective housing and connected to the generator. For coagulant storage, two or three 208 liter drums will provide sufficient coagulant for major storms.

An alternative, but less accurate method, would be to use a rain gauge transmitter connected directly to the controller. This method would estimate the input runoff flow rate into the basin based on rainfall, rather than measuring it directly. This method should be used in the event that a weir cannot be installed to the inflow.

The digital dispenser will be calibrated for dosing based on the laboratory tests of the chosen coagulant. Based on the input flow rate of the channel, enough coagulant will be pumped so as to provide the proper dose for all of the runoff entering the basin. Figure 5.3 illustrates the setup required for implementation.

Once the field test equipment is installed, monitoring can be conducted through sampling. Comparative studies can be done by also sampling the basin without coagulant addition. Grab samples can be collected from the beginning of the input channel (prior to coagulant addition), where the input channel enters the basin, and at the outflow during

a rainfall event. Samples should also be collected from various points throughout the basin, especially prior to the outflow. Sampling should begin soon after rainfall begins and be taken every hour during the rainfall duration, preferably for a minimum of 6 hours. Sample bottles should be 500 mL for easy transport and testing. These samples should be tested for TSS, TDS, and Turbidity using Standard Methods.

The above installation design is easily adaptable for use as a standard coagulant-assisted construction site sedimentation basin. Only the sampling instructions do not apply. A technician is still required to perform all of the duties listed above with the exception of sampling.

5.4. Dosing Formula

Calculating the correct dosage of coagulant depends on several factors. First the flow rate entering the riprap inflow must be known. Without a flow meter, this value can be calculated using a rain gauge and knowledge of the drainage area for the basin. The Rational Formula can be used as a simple estimate (Chin 2000):

$$Q = CiA \tag{5.4}$$

where Q is equal to the stormwater runoff flow rate entering the inlet, C is the runoff coefficient, i is the rainfall intensity, and A is the drainage area. The

runoff coefficient is dependent on the composition of the drainage area and for construction sites is likely to be 0.3-0.6 (Goldman et al. 1986), the value for smooth bare, packed soil.

Once the flow rate entering the basin is known, the coagulant flow can be calculated with the target coagulant dose and the coagulant stock solution concentration.

$$Q_d = \frac{QC_d}{C_s} = \frac{CiAC_d}{C_s} \tag{5.5}$$

where Q_d is the flow rate of the coagulant, Q is the stormwater runoff flow rate entering the basin, C_d is the target dose concentration found from lab studies, and C_s is the coagulant stock solution concentration.

The rainfall intensity measured by the rain gauge or the flow rate measured by the flow sensor should be updated at intervals of 3-5 minutes or less. At longer intervals, changes in rainfall intensity could cause inappropriate doses to affect the efficiency of the system.

5.4.1. Sample Calculation

An example of this calculation would assume a disturbed drainage area of 8000 m^2. Laboratory studies with coagulant have shown that 2 mg/L of anionic polyacrylamide is an effective coagulant. The stock solution of coagulant onsite is 1000 mg/L. Assume that the runoff coefficient for the construction site is 0.45 (Goldman et al. 1986), meaning that 45% of the rainfall becomes runoff. The rain begins and is measured at an intensity of 0.5 in/hr which converts to 3.5 x 10^{-6} m/s.

$$Q = CiA = (0.45)(3.5 \times 10^{-6} \text{ m/s})(8000 \text{ m}^2) = 0.0126 \text{ m}^3/\text{s} \quad (5.6)$$

$$\frac{C_d}{C_s} = (2 \text{ mg/L})/(1000 \text{ mg/L}) = 0.002 \quad (5.7)$$

$$Q_d = \frac{QC_d}{C_s} = (0.0126 \text{ m}^3/\text{s})(0.002) = 2.5 \times 10^{-5} \text{ m}^3/\text{s} = 25 \text{ mL/s} \quad (5.8)$$

Thus, the pump would be set to emit coagulant at a flow rate of 25 mL/s until the rainfall intensity changes. The added coagulant would be mixed into the runoff as it flows through the riprap.

5.5. Comparison with other systems

This field testing design proposed here differs significantly from the method used in New Zealand (Auckland Regional Council 2003). Their

method captured rainfall in a catchment tray which drained to a header tank. The header tank drained to a displacement tank which floated in a coagulant reservoir. As the displacement tank filled, it sunk deeper into the coagulant reservoir and coagulant was released into the basin at the inlet.

The New Zealand system was efficient at reducing turbidity, but it is a primitive system. For example, the catchment tray and displacement tank are based on specific site conditions of drainage area and 2-year rainfall, respectively. That system must be reconstructed at every basin, whereas the automated design proposed here can be easily replicated or transported between basins. Also, it was noted in the New Zealand study that after 7 day dry spells, there would be a delay in coagulant dosing due to the startup mechanism of the header tank. This led to significant amounts of sediment overflowing the basin. The automated system begins immediately when rainfall begins and adjusts immediately to changes in storm intensity.

The automated dosing system is not recommended for low flow rates during light rainfalls. In these circumstances, the sedimentation basins are generally efficient as designed. Also, if the coagulant-added runoff enters the riprap at low flow rates, settling could begin before runoff reaches the basin. At high flow rates there is likely sufficient turbulence to maintain particle suspension through the riprap.

Chapter 6. Conclusions and Recommendations

Based on the laboratory data collected from the Rt. 43 White Marsh site, coagulants can be effective for reducing suspended solids and turbidity in stormwater basins. For anionic polyacrylamide, doses of 2 mg/L or less were the most effective. Cationic polyacrylamides worked best with doses between 6 and 10 mg/L. Alum performed best at doses over 60 mg/L. For this particular site, alum and C-448 were the most effective coagulants in both removing suspended solids and lowering turbidity. However, literature data suggests that soils can be variable in their interactions with coagulants and what is effective at one site may not be at another. Also, efficiency of the TSS removal and turbidity reduction are only part of the considerations that must be made before choosing a coagulant for field use in construction site sedimentation basins. Dosing concentrations, toxicity, and maintenance must also be considered. A protocol was developed that describes the process by which to best choose a coagulant for use in stormwater basins. A field testing design has also been included and outlines the implementation and calculations to be made for successful field testing.

Anionic polyacrylamides were variable in effectiveness at reducing TSS and turbidity in construction site stormwater. The polymers tested

varied in molecular weight and anionic charge. The polymers A-100 and A-110 were chosen as the top performing anionic polymers for the comparison study at doses of 2 mg/L. They both have high molecular weight and low anionic charge. The charges are –7% and –16%, respectively. Anionic polymer A-100 was successful at increasing TSS removal from averages of 88% to 96% and increasing turbidity removal from 51% to 78%. The polymer A-110 was slightly less effective in both TSS and turbidity removal reducing by averages of 95% and 72%, respectively.

Cationic polyacrylamides produced consistent results at reducing TSS and turbidity in construction site stormwater. The cationic polymers tested varied in cationic charge and molecular weight. The high molecular weight polymers were more effective than the polymers with medium molecular weights. Those with medium molecular weights had removal ratios consistent with anionic polymers, while high molecular weight cationic polymers were more effective in both TSS and turbidity removal than anionic polymers. The polymer C-448 was chosen for the coagulant comparison study at a dose of 6 mg/L. It has a high molecular weight and +35% charge. C-448 increased average TSS removal from 88% to 97% and average turbidity reduction from 50% to 85%. In our study site, C-448 was the most efficient reducer of turbidity and equaled the TSS reduction of alum.

Alum was consistently effective at removing suspended solids and reducing turbidity in construction site stormwater. Using alum at a dose of 100 mg/L, an average of 97% of TSS was removed compared to 88% without coagulant. Turbidity was reduced by over an average of 84% compared to only 51% without a coagulant. Alum was more effective than anionic polyacrylamide at TSS removal and reduction of turbidity and equaled the TSS removal of C-448 cationic polymer.

The dosing concentration of the coagulant can determine the selection for field use at a construction site sedimentation basin. Anionic polyacrylamides were effective at lower doses than cationic polyacrylamides and significantly lower doses than alum. Lower coagulant doses can be beneficial during field usage. At very high doses, such as those for alum, problems may arise with the stock solution. Either the stock concentration must be very high or vast storage space must be available. High stock concentrations can create very viscous solutions that could be difficult to use onsite. The coagulant flow rate is proportional to the runoff flow rate by the ratio of target concentration to stock concentration. If this ratio is more than a few percent, the additional flow rate into the basin could be problematic, especially during intense storm events.

The potential toxicity of a coagulant must also be considered during field usage. Studies in the literature have shown cationic polyacrylamides to be toxic to aquatic organisms even at low doses and are not recommended for field use. Anionic polyacrylamides have been shown to be nontoxic as long as they retain the poly-chain structure. The acrylamide monomer is a severe neurotoxin, but the breakdown of polyacrylamide into the monomer is very rare. Alum is nontoxic at low solubility concentrations. These concentrations occur between pH 5.5 and 7.5. A pH study should be conducted to prevent unsafe usage of alum in stormwater runoff.

Maintenance issues can arise when coagulants are effective in sedimentation basins. Basins must be dredged if the sediment load that has settled on the bottom reaches a certain level. With the addition of coagulants, the volume of settled sediment has the potential to increase and force dredging to be more frequent. This could be an additional cost for the construction site.

A field coagulant delivery system was developed, but not tested. The system was designed to automatically pump coagulant into the riprap inlet upon the start of rainfall. The riprap acts as a rapid mix process before runoff reaches the sedimentation basin. The width and slope were determined to be design parameters for a rapid mix riprap inlet. A coagulant dosing

calculation was developed for use in programming the automated system. To work efficiently, the coagulant selection protocol should be followed to choose the most effective coagulant type and dosage for the site.

This study provides important information about the potential for coagulant-assisted stormwater basins for active road construction sites. Laboratory data demonstrated the efficacy of several coagulants for this use. The removal of additional suspended solids and reduced turbidity can greatly lessen the pollutant load entering water bodies near active construction sites. Continued research with field testing of coagulant-assisted sedimentation basins will provide better knowledge of the feasibility for widespread use. The next research step would be to perform field trials in multiple field situations. Once consistency has been obtained, integration of the dosing system from individual pieces to one connected integrated instrument would be very useful for promoting widespread usage.

Appendix

Units for all charts: TSS, TS, coagulant dose = mg/L; Vol = mL; weights = g; Turbidity = NTUs

Field Test May 5, 2005

TSS Data Table

	Hour 1	Hour 2	Hour 3	Average	St Dev
6I	38.2	57.1	70.0	55.1	15.99406
6P	30.0	52.8	44.0	42.3	11.49841
6O	90.0	39.6	48.0	59.2	27.00222
7I	351.0	208.7	232.6	264.1	76.20046
7P	39.2	88.9	50.0	59.4	26.14045
7O	48.9	55.8	65.9	56.9	8.550049
8I	81.1	142.6	147.1	123.6	36.87479
8P	82.6	43.9	47.1	57.9	21.47937
8O	69.1	64.2	53.5	62.3	7.977677
9I	794.9	1055.9	1041.5	964.1	146.7083
9P	848.8	1033.3	756.8	879.6	140.8051
9O	1147.1	625.0	176.1	649.4	485.9596

I Inlet
P Pipe
O Outlet

Field Test June 3, 2005

Hour	Location	Filter Wt	Total Wt	Vol	TSS		Location	Filter Wt	Total Wt	Vol	TSS
	7I	1.1047	1.1063	53	30		6I	1.0959	1.0963	78	5
1	7P	1.0973	1.0986	70	19		6P	1.1086	1.1106	72	28
	7O	1.1020	1.1037	60	28		6O	1.0898	1.0908	73	14
	7I	1.0948	1.0971	57	40		6I	1.0968	1.0978	74	14
2	7P	1.0975	1.0999	59	41		6P	1.0925	1.0932	68	10
	7O	1.1065	1.1083	57	32		6O	1.0947	1.1052	53	198
	7I	1.0917	1.1014	54	180		6I	1.0917	1.0920	71	4
3	7P	1.0978	1.0993	62	24		6P	1.0949	1.0965	57	28
	7O	1.0962	1.0979	57	30						
	7I	1.0989	1.1032	58	74		6I	1.1002	1.1015	72	18
4	7P	1.1019	1.1032	59	22		6P	1.0960	1.0979	64	30
	7O	1.0917	1.0928	68	16						
	7I	1.0941	1.0971	58	52		6I	1.1044	1.1060	73	22
5	7P	1.0975	1.0991	59	27		6P	1.1036	1.1052	69	23
	7O	1.1057	1.1077	64	31						
	7I	1.0996	1.1063	58	116		6I	1.1037	1.1044	61	11
6	7P	1.1001	1.1012	59	19		6P	1.0935	1.0951	72	22
	7O	1.1041	1.1056	53	28						

PAM Lab Trial Superfloc N-300 Basin 9 June 28, 2005

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0913	1.093	41	41.46341	39.0214	39.0342	41	312.1951		353.6585
0.5	1.0995	1.1011	40	40	38.5214	38.5323	40	272.5		312.5
1	1.1033	1.1059	40	65	36.8069	36.8177	40	270		335
2	1.0983	1.1005	42	52.38095	36.3159	36.3269	42	261.9048		314.2857

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1023	1.1025	40	5	30.9575	30.9686	40	277.5		282.5
0.5	1.0973	1.0976	35	8.571429	28.1028	28.1114	35	245.7143		254.2857
1	1.1076	1.1085	32	28.125	29.5263	29.535	32	271.875		300
2	1.0971	1.0981	31	32.25806	28.743	28.7503	31	235.4839		267.7419

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1045	1.1046	34	2.941176	33.4846	33.4931	34	250		252.9412
0.5	1.1026	1.1028	35	5.714286	32.9721	32.981	35	254.2857		260
1	1.098	1.0983	35	8.571429	33.8881	33.8958	35	220		228.5714
2	1.0923	1.0927	34	11.76471	35.0426	35.0499	34	214.7059		226.4706

Turbidity after 24 hours

PAM conc	NTU
0	60
0.5	50
1	50
2	55

PAM lab trial Superfloc A-110 Basin 9 June 28, 2005

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.096	1.0967	42	16.66667	36.8025	36.8172	42	350		366.6667
0.5	1.098	1.0986	41	14.63415	39.02	39.0347	41	358.5366		373.1707
1	1.1046	1.1055	41	21.95122	38.5194	38.5315	41	295.122		317.0732
2	1.1015	1.1026	40	27.5	36.3151	36.3267	40	290		317.5

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0935	1.0936	34	2.941176	28.1001	28.1093	34	270.5882		273.5294
0.5	1.0959	1.0963	35	11.42857	29.525	29.5338	35	251.4286		262.8571
1	1.0941	1.0951	34	29.41176	30.9576	30.9658	34	241.1765		270.5882
2	1.104	1.1052	34	35.29412	28.7431	28.7506	34	220.5882		255.8824

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1019	1.1022	35	8.571429	33.885	33.8966	35	331.4286		340
0.5	1.0993	1.1	35	20	32.9701	32.9798	35	277.1429		297.1429
1	1.1019	1.1026	32	21.875	33.4834	33.4914	32	250		271.875
2	1.1064	1.1068	32	12.5	29.5247	29.532	32	228.125		240.625

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	55
0.5	55
1	60
2	55

PAM lab trial Superfloc A-120 Basin 8 July 5, 2005

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0982	1.1087	38	276.3158	33.8872	33.9015	38	376.3158		652.6316
0.5	1.097	1.109	40	300	29.5259	29.5405	40	365		665
1	1.0949	1.1076	42	302.381	33.4881	33.5009	42	304.7619		607.1429
2	1.0978	1.1081	39	264.1026	32.9716	32.9859	39	366.6667		630.7692

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1007	1.1032	37	67.56757	28.1009	28.114	37	354.0541		421.6216
0.5	1.1041	1.1066	36	69.44444	35.039	35.0498	36	300		369.4444
1	1.0907	1.0932	35	71.42857	30.9589	30.97	35	317.1429		388.5714
2	1.111	1.115	37	108.1081	29.6119	29.6242	37	332.4324		440.5405

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0961	1.0962	36	2.777778	32.9707	32.9853	36	405.5556		408.3333
0.5	1.0948	1.0954	36	16.66667	33.4839	33.4977	36	383.3333		400
1	1.0917	1.0919	36	5.555556	33.8869	33.9005	36	377.7778		383.3333
2	1.1061	1.1068	38	18.42105	29.5255	29.5397	38	373.6842		392.1053

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	8.1
0.5	5.2
1	6
2	8.5

PAM lab trial Superfloc A-100 Basin 8 July 5, 2005

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0985	1.1131	38	384.2105	33.4846	33.4968	38	321.0526		705.2632
0.5	1.1012	1.1172	39	410.2564	29.5365	29.5426	39	156.4103		566.6667
1	1.0928	1.1118	41	463.4146	32.9717	32.9846	41	314.6341		778.0488
2	1.1047	1.1212	42	392.8571	33.8876	33.9053	42	421.4286		814.2857

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0981	1.1013	33	96.9697	30.9585	30.9687	33	309.0909		406.0606
0.5	1.1087	1.1096	34	26.47059	35.0385	35.052	34	397.0588		423.5294
1	1.1044	1.1053	34	26.47059	28.1012	28.1113	34	297.0588		323.5294
2	1.0989	1.1003	33	42.42424	29.612	29.6241	33	366.6667		409.0909

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0937	1.0947	35	28.57143	30.9582	30.9725	35	408.5714		437.1429
0.5	1.0992	1.1003	35	31.42857	33.4858	33.4992	35	382.8571		414.2857
1	1.095	1.096	33	30.30303	32.972	32.985	33	393.9394		424.2424
2	1.1032	1.1047	34	44.11765	28.1016	28.1145	34	379.4118		423.5294

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	15
0.5	6.5
1	6.8
2	8.1

PAM lab trial Superfloc A-130 Basin 9 July 20, 2005

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0998	1.1057	35	168.5714	29.6129	29.6303	35	497.1429		665.7143
0.5	1.093	1.0992	35	177.1429	29.5275	29.5442	35	477.1429		654.2857
1	1.1049	1.1119	36	194.4444	35.0396	35.056	36	455.5556		650
2	1.1016	1.1075	33	178.7879	33.8896	33.9056	33	484.8485		663.6364

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.105	1.108	37	81.08108	30.9594	30.9764	37	459.4595		540.5405
0.5	1.0929	1.1085	38	410.5263	33.4858	33.49	38	110.5263		521.0526
1	1.0964	1.1121	34	461.7647	32.9727	32.9743	34	47.05882		508.8235
2	1.1018	1.1192	33	527.2727	28.1028	28.1047	33	57.57576		584.8485

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0995	1.1003	34	23.52941	28.1007	28.1156	34	438.2353		461.7647
0.5	1.0971	1.1002	34	91.17647	32.9723	32.9822	34	291.1765		382.3529
1	1.1019	1.1087	34	200	33.4848	33.4896	34	141.1765		341.1765
2	1.096	1.1077	35	334.2857	30.9584	30.9635	35	145.7143		480

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	55
0.5	55
1	60
2	50

PAM lab trial Superfloc A-150 Basin 9 July 20, 2005

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0962	1.1047	38	223.6842	29.526	29.5427	38	439.4737		663.1579
0.5	1.1065	1.1146	36	225	33.8882	33.9053	36	475		700
1	1.095	1.1036	36	238.8889	35.042	35.0599	36	497.2222		736.1111
2	1.0968	1.107	36	283.3333	29.6102	29.6264	36	450		733.3333

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1024	1.1061	36	102.7778	30.9589	30.9752	36	452.7778		555.5556
0.5	1.1016	1.1143	35	362.8571	28.1014	28.1075	35	174.2857		537.1429
1	1.0943	1.1078	36	375	33.4851	33.4907	36	155.5556		530.5556
2	1.0946	1.1098	35	434.2857	32.9722	32.977	35	137.1429		571.4286

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0985	1.0991	34	17.64706	29.525	29.538	34	382.3529		400
0.5	1.0984	1.0999	34	44.11765	33.8867	33.896	34	273.5294		317.6471
1	1.1026	1.104	34	41.17647	32.9716	32.98	34	247.0588		288.2353
2	1.0898	1.0936	33	115.1515	30.9582	30.963	33	145.4545		260.6061

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	55
0.5	60
1	55
2	55

A-150 Lab Trial 2 Basin 8 10/10/05

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0998	1.1123	34	367.64706	68.2084	68.2165	34	238.23529		605.88235
2	1.1027	1.1153	37	340.54054	74.9428	74.9524	37	259.45946		600
4	1.0909	1.1052	37	386.48649	64.5149	64.5234	37	229.72973		616.21622
6	1.1019	1.114	36	336.11111	61.9907	62.0005	36	272.22222		608.33333
8	1.1038	1.1155	34	344.11765	61.2686	61.2778	34	270.58824		614.70588
10	1.096	1.1085	35	357.14286	63.4582	63.4662	35	228.57143		585.71429

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1024	1.1166	35	405.71429	33.4785	33.4855	35	200		605.71429
2	1.0966	1.1052	33	260.60606	35.0322	35.0356	33	103.0303		363.63636
4	1.0968	1.1097	34	379.41176	33.8812	33.8847	34	102.94118		482.35294
6	1.0877	1.1017	34	411.76471	29.5205	29.5245	34	117.64706		529.41176
8	1.098	1.1109	31	416.12903	32.9661	32.9692	31	100		516.12903
10	1.0961	1.1102	32	440.625	30.9528	30.9592	32	200		640.625

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1007	1.1054	34	138.23529	64.5093	64.5188	34	279.41176		417.64706
2	1.1011	1.1041	35	85.714286	74.9386	74.9412	35	74.285714		160
4	1.0881	1.0933	34	152.94118	68.2073	68.2092	34	55.882353		208.82353
6	1.0849	1.0927	35	222.85714	61.2665	61.2668	35	8.5714286		231.42857
8	1.0977	1.1066	35	254.28571	61.9924	61.9926	35	5.7142857		260
10	1.0941	1.1026	31	274.19355	63.4593	63.4595	31	6.4516129		280.64516

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	120
2	70
4	80
6	100
8	110
10	120

Alum Lab Trial Basin 9 10/10/05

Before Alum addition

Alum conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1039	1.115	36	308.33333	29.5194	29.5294	36	277.77778		586.11111
20	1.0992	1.1089	36	269.44444	32.9648	32.9764	36	322.22222		591.66667
40	1.092	1.1031	34	326.47059	33.8803	33.8913	34	323.52941		650
60	1.0968	1.11	35	377.14286	35.0319	35.0412	35	265.71429		642.85714
80	1.0922	1.1048	34	370.58824	33.4793	33.4884	34	267.64706		638.23529
100	1.1035	1.1175	35	400	30.9535	30.9618	35	237.14286		637.14286

2 hours settling

Alum conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0941	1.1049	34	317.64706	74.9345	74.9502	34	461.76471		779.41176
20	1.1002	1.1135	35	380	68.2047	68.2147	35	285.71429		665.71429
40	1.1006	1.1117	33	336.36364	64.5113	64.5185	33	218.18182		554.54545
60	1.0976	1.1008	33	96.969697	61.9876	61.9933	33	172.72727		269.69697
80	1.0987	1.1004	35	48.571429	61.267	61.2732	35	177.14286		225.71429
100	1.1073	1.1087	35	40	63.4582	63.4637	35	157.14286		197.14286

24 hours settling

Alum conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1058	1.1092	34	100	35.0302	35.0418	34	341.17647		441.17647
20	1.0973	1.1018	34	132.35294	32.9645	32.9713	34	200		332.35294
40	1.0956	1.0985	33	87.878788	29.5195	29.525	33	166.66667		254.54545
60	1.1033	1.1042	36	25	33.4774	33.4827	36	147.22222		172.22222
80	1.0879	1.0883	33	12.121212	30.953	30.957	33	121.21212		133.33333
100	1.092	1.0922	33	6.0606061	33.8818	33.8858	33	121.21212		127.27273

Turbidity after 24 hours

Alum conc	Turb (ntu)
0	130
20	120
40	80
60	20
80	5
100	4

pH after 24 hours

Alum conc	pH
0	6.28
20	6.64
40	6.36
60	6.2
80	6.28
100	6.25

Alum Lab Trial Basin 8 10/22/05

Before Alum addition

Alum	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0823	1.0833	35	28.571429	32.9659	32.9708	35	140		168.57143
20	1.099	1.1002	36	33.333333	33.4777	33.4827	36	138.88889		172.22222
40	1.0849	1.086	35	31.428571	29.5209	29.5261	35	148.57143		180
60	1.0995	1.1007	36	33.333333	35.0322	35.0377	36	152.77778		186.11111
80	1.0992	1.1004	35	34.285714	30.9533	30.9581	35	137.14286		171.42857
100	1.0927	1.0941	36	38.888889	33.8815	33.8874	36	163.88889		202.77778

2 hours settling

Alum	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1068	1.1073	35	14.285714	74.9443	74.9499	35	160		174.28571
20	1.1044	1.1052	34	23.529412	64.5145	64.5199	34	158.82353		182.35294
40	1.095	1.0968	34	52.941176	61.9906	61.9957	34	150		202.94118
60	1.0966	1.0972	35	17.142857	61.2675	61.2726	35	145.71429		162.85714
80	1.1007	1.1011	34	11.764706	63.4588	63.4637	34	144.11765		155.88235
100	1.0955	1.0958	34	8.8235294	68.2088	68.2138	34	147.05882		155.88235

24 hours settling

Alum	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.0984	1.0989	35	14.285714	29.5168	29.525	35	234.28571		248.57143
20	1.1026	1.1034	34	23.529412	35.0288	35.0371	34	244.11765		267.64706
40	1.085	1.0861	34	32.352941	33.8793	33.886	34	197.05882		229.41176
60	1.0925	1.093	34	14.705882	32.9639	32.9699	34	176.47059		191.17647
80	1.1059	1.1062	34	8.8235294	33.4768	33.4825	34	167.64706		176.47059
100	1.0894	1.0893	35	-2.8571429	30.9519	30.9574	35	157.14286		154.28571

Turbidity after 24 hours

Alu	Turb (ntu)
0	23
20	25
40	23
60	3.5
80	3
100	2.5

A-130V Lab Trial Basin 6 11/23/05

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1019	1.1038	35	54.285714	63.4563	63.4732	35	482.85714		537.14286
2	1.1015	1.1035	35	57.142857	61.9886	62.0059	35	494.28571		551.42857
4	1.0964	1.0986	38	57.894737	61.2655	61.2863	38	547.36842		605.26316
6	1.1072	1.1096	38	63.157895	64.5138	64.5328	38	500		563.15789
8	1.1012	1.1032	34	58.823529	74.9411	74.958	34	497.05882		555.88235
10	1.1053	1.1074	36	58.333333	68.207	68.2243	36	480.55556		538.88889

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1082	1.1088	37	16.216216	32.9654	32.981	37	421.62162		437.83784
2	1.1066	1.1072	35	17.142857	35.0329	35.0472	35	408.57143		425.71429
4	1.0977	1.0983	34	17.647059	30.9527	30.9661	34	394.11765		411.76471
6	1.0914	1.0923	35	25.714286	33.8817	33.8962	35	414.28571		440
8	1.0994	1.1003	34	26.470588	33.4784	33.4901	34	344.11765		370.58824
10	1.106	1.1068	34	23.529412	29.5216	29.5356	34	411.76471		435.29412

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1029	1.1035	36	16.666667	68.2052	68.2215	36	452.77778		469.44444
2	1.1009	1.1017	34	23.529412	74.9422	74.9582	34	470.58824		494.11765
4	1.101	1.1018	34	23.529412	63.457	63.4731	34	473.52941		497.05882
6	1.11	1.1108	34	23.529412	61.9921	62.0068	34	432.35294		455.88235
8	1.1069	1.1077	34	23.529412	61.2675	61.2821	34	429.41176		452.94118
10	1.102	1.1031	35	31.428571	64.5165	64.53	35	385.71429		417.14286

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	6.5
2	6
4	6.5
6	6
8	7
10	6.5

C-446 Lab Trial Basin 9 11/23/05

Before PAM addition

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.1067	1.1082	35	42.857143	33.4772	33.4836	35	182.85714		225.71429
2	1.104	1.1057	35	48.571429	29.519	29.5253	35	180		228.57143
4	1.0988	1.1008	37	54.054054	30.9512	30.9579	37	181.08108		235.13514
6	1.1033	1.1048	35	42.857143	33.8806	33.8866	35	171.42857		214.28571
8	1.1052	1.1071	36	52.777778	35.0309	35.0371	36	172.22222		225
10	1.1033	1.1053	36	55.555556	32.9645	32.9709	36	177.77778		233.33333

2 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.099	1.1002	37	32.432432	61.9886	61.989	37	10.810811		43.243243
2	1.099	1.1003	34	38.235294	61.2659	61.266	34	2.9411765		41.176471
4	1.1001	1.1013	33	36.363636	64.5129	64.5133	33	12.121212		48.484848
6	1.0996	1.101	35	40	68.2063	68.2078	35	42.857143		82.857143
8	1.0898	1.0906	34	23.529412	63.4569	63.4574	34	14.705882		38.235294
10	1.1004	1.1016	34	35.294118	74.9414	74.9434	34	58.823529		94.117647

24 hours settling

PAM conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
0	1.106	1.1064	34	11.764706	30.9475	30.9559	34	247.05882		258.82353
2	1.095	1.0956	33	18.181818	33.4746	33.4814	33	206.06061		224.24242
4	1.1083	1.1086	34	8.8235294	29.5186	29.5243	34	167.64706		176.47059
6	1.104	1.1045	36	13.888889	35.0299	35.0357	36	161.11111		175
8	1.0863	1.0863	35	0	32.9631	32.969	35	168.57143		168.57143
10	1.0988	1.0991	34	8.8235294	33.8796	33.885	34	158.82353		167.64706

Turbidity after 24 hours

PAM conc	Turb (ntu)
0	10
2	10
4	6
6	5
8	1
10	6

Coagulant Lab Trial 1 Basin 7 4/14/06

Before coagulant addition

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.1016	1.1455	38	1155.263	30.9525	30.9739	38	563.1579		1718.421
A-100 2mg/L	1.1035	1.1502	35	1334.286	35.033	35.0522	35	548.5714		1882.857
A-110 2 mg/L	1.106	1.1505	37	1202.703	28.0944	28.1081	37	370.2703		1572.973
C-448 6 mg/L	1.108	1.1473	35	1122.857	29.5218	29.539	35	491.4286		1614.286
Alum 100 mg/L	1.1059	1.1446	36	1075	29.6024	29.6215	36	530.5556		1605.556

30 minutes settling

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.1052	1.1102	43	116.2791	81.7088	81.731	43	516.2791		632.5581
A-100 2mg/L	1.0943	1.0974	39	79.48718	64.5199	64.541	39	541.0256		620.5128
A-110 2 mg/L	1.0989	1.1044	51	107.8431	61.9911	62.0171	51	509.8039		617.6471
C-448 6 mg/L	1.0973	1.0989	46	34.78261	68.2139	68.2348	46	454.3478		489.1304
Alum 100 mg/L	1.1103	1.1129	48	54.16667	63.464	63.4839	48	414.5833		468.75

Turbidity before coagulant addition

coagulant conc	Turb (ntu)
none	55
A-100 2mg/L	60
A-110 2 mg/L	70
C-448 6 mg/L	70
Alum 100 mg/L	60

Turbidity after 30 minutes settling

coagulant conc	Turb (ntu)
none	20
A-100 2mg/L	12
A-110 2 mg/L	18
C-448 6 mg/L	9
Alum 100 mg/L	10

Coagulant Lab Trial 2 Basin 7 4/14/06 Trial 2

Before coagulant addition

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.0941	1.1488	37	1478.378	28.1003	28.117	37	451.3514		1929.73
A-100 2mg/L	1.1048	1.175	36	1950	29.6109	29.6263	36	427.7778		2377.778
A-110 2 mg/L	1.1041	1.1754	36	1980.556	29.5302	29.5462	36	444.4444		2425
C-448 6 mg/L	1.0943	1.1801	41	2092.683	35.0428	35.0606	41	434.1463		2526.829
Alum 75 mg/L	1.1022	1.159	35	1622.857	30.9645	30.9801	35	445.7143		2068.571

30 minutes settling

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.1111	1.1208	50	194	64.5316	64.5532	50	432		626
A-100 2mg/L	1.0982	1.1012	50	60	68.227	68.2455	50	370		430
A-110 2 mg/L	1.1038	1.1074	49	73.46939	81.7246	81.7439	49	393.8776		467.3469
C-448 6 mg/L	1.1038	1.1056	49	36.73469	63.4775	63.4956	49	369.3878		406.1224
Alum 75 mg/L	1.1008	1.1028	50	40	62.0089	62.0245	50	312		352

Turbidity before coagulant addition			Turbidity after 30 minutes settling	
coagulant conc	Turb (ntu)		coagulant conc	Turb (ntu)
none	80		none	45
A-100 2mg/L	80		A-100 2mg/L	18
A-110 2 mg/L	80		A-110 2 mg/L	18
C-448 6 mg/L	85		C-448 6 mg/L	11
Alum 75 mg/L	80		Alum 75 mg/L	10

Coagulant Lab Trial 3 Basin 7 4/14/06

Before coagulant addition

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.1029	1.1703	35	1925.714	29.5363	29.554	35	505.7143		2431.429
A-100 2mg/L	1.101	1.1878	36	2411.111	29.6172	29.636	36	522.2222		2933.333
A-110 2 mg/L	1.0998	1.2362	37	3686.486	35.0483	35.0677	37	524.3243		4210.811
C-448 6 mg/L	1.1062	1.1993	36	2586.111	28.1045	28.1255	36	583.3333		3169.444
Alum 100 mg/L	1.1063	1.1847	35	2240	30.9707	30.988	35	494.2857		2734.286

30 minutes settling

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.097	1.1066	49	195.9184	81.7375	81.7585	49	428.5714		624.4898
A-100 2mg/L	1.0961	1.1002	51	80.39216	62.0204	62.0418	51	419.6078		500
A-110 2 mg/L	1.1017	1.1064	51	92.15686	63.4923	63.5166	51	476.4706		568.6275
C-448 6 mg/L	1.1037	1.1047	51	19.60784	68.2377	68.2622	51	480.3922		500
Alum 100 mg/L	1.1036	1.1062	51	50.98039	64.5418	64.565	51	454.902		505.8824

Turbidity before coagulant addition Turbidity after 30 minutes settling

coagulant conc	Turb (ntu)		coagulant conc	Turb (ntu)
none	85		none	40
A-100 2mg/L	90		A-100 2mg/L	20
A-110 2 mg/L	85		A-110 2 mg/L	28
C-448 6 mg/L	80		C-448 6 mg/L	9.5
Alum 100 mg/L	90		Alum 100 mg/L	15

Coagulant Lab Trial 4 Basin 7 4/14/06

Before coagulant addition

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.1053	1.1675	34	1829.412	30.9783	30.9973	34	558.8235		2388.235
A-100 2mg/L	1.0992	1.1596	35	1725.714	29.5423	29.5621	35	565.7143		2291.429
A-110 2 mg/L	1.1018	1.1715	36	1936.111	28.1127	28.1352	36	625		2561.111
C-448 6 mg/L	1.1042	1.166	33	1872.727	29.6233	29.6162	33	-215.152		1657.576
Alum 100 mg/L	1.1016	1.1751	36	2041.667	35.0555	35.0773	36	605.5556		2647.222

30 minutes settling

coagulant conc	Initial	Final	Vol	TSS	Initial	Final	Vol	TDS		TS
none	1.1076	1.1198	45	271.1111	64.5563	64.582	45	571.1111		842.2222
A-100 2mg/L	1.0882	1.0928	45	102.2222	62.0298	62.0529	45	513.3333		615.5556
A-110 2 mg/L	1.1029	1.109	51	119.6078	68.2497	68.2772	51	539.2157		658.8235
C-448 6 mg/L	1.0989	1.1032	49	87.7551	81.7459	81.7695	49	481.6327		569.3878
Alum 100 mg/L	1.1015	1.1049	51	66.66667	63.4995	63.5288	51	574.5098		641.1765

Turbidity before coagulant addition

coagulant conc	Turb (ntu)
none	95
A-100 2mg/L	95
A-110 2 mg/L	95
C-448 6 mg/L	90
Alum 100 mg/L	90

Turbidity after 30 minutes settling

coagulant conc	Turb (ntu)
none	55
A-100 2mg/L	25
A-110 2 mg/L	30
C-448 6 mg/L	20
Alum 100 mg/L	15

pH study 5/4/06 Basin 7

No Coagulant

pH	Initial	Final	Vol	TSS	Turbidity
5.66	1.3745	1.4967	51	2396.0784	85
6.5	1.1041	1.1916	53	1650.9434	80
7.45	1.1036	1.2021	50	1970	100
8	1.0919	1.1969	50	2100	80
After 30 minutes					
5.66	1.1022	1.1176	49	314.28571	55
6.5	1.1004	1.1151	51	288.23529	45
7.45	1.104	1.1223	48	381.25	65
8	1.3801	1.3922	47	257.44681	50

C-448

pH	Initial	Final	Vol	TSS	Turbidity
5.66	1.1021	1.2265	51	2439.2157	85
6.5	1.097	1.2116	52	2203.8462	80
7.45	1.1012	1.202	52	1938.4615	100
8	1.1102	1.2015	50	1826	85
After 30 minutes					
5.66	1.1038	1.1079	50	82	20
6.5	1.0947	1.0981	52	65.384615	12
7.45	1.0864	1.0889	46	54.347826	12
8	1.1103	1.1128	49	51.020408	12

A-100

pH	Initial	Final	Vol	TSS	Turbidity
5.66	1.382	1.5256	49	2930.6122	85
6.5	1.1072	1.2152	48	2250	80
7.45	1.1009	1.2133	50	2248	100
8	1.375	1.4821	46	2328.2609	85
After 30 minutes					
5.66	1.1031	1.1109	50	156	35
6.5	1.1021	1.1099	51	152.94118	20
7.45	1.1002	1.1063	47	129.78723	30
8	1.3858	1.3913	49	112.2449	25

Alum

pH	Initial	Final	Vol	TSS	Turbidity
5.66	1.3646	1.5117	50	2942	95
6.5	1.1065	1.2333	52	2438.4615	80
7.45	1.1016	1.2205	50	2378	100
8	1.1061	1.1938	53	1654.717	85
After 30 minutes					
5.66	1.3881	1.3922	52	78.846154	20
6.5	1.1038	1.1069	52	59.615385	10
7.45	1.1098	1.1133	52	67.307692	12
8	1.0962	1.0989	48	56.25	12

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